THIRD EDITION : CD INCLUDED

APPLIED BALLISTICS FOR LONG-RANGE SHOOTING

Understanding the Elements and Application of External Ballistics for Successful Long-Range Target Shooting and Hunting

BRYAN LITZ

Applied Ballistics for
Long Range Shooting
Third Edition

By Bryan Litz

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This book is dedicated to my Parents

To my Dad,
Who taught me how to shoot,
and that 2+2 is *always* 4.

And to my Mom,
Who's always encouraged and supported
my pursuit of happiness.

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Introduction

There are a number of books on the subject of external ballistics. Most of them seem to fall into one of two categories: they're either too technical or they're not technical enough. The books in the *too technical* category are filled with equations and mathematical derivations intended to represent the state of the art in academic vernacular. In that respect, the books are a success; however few shooters are able to extract very much *practical* information that can be directly applied to improve their shooting. On the other end of the spectrum are the shooting books that aren't technical enough. The books I'm referring to usually talk about all aspects of shooting, with perhaps one chapter on exterior ballistics. Although well rounded and useful for teaching beginners about the many aspects of shooting, these books usually only scratch the surface of external ballistics.

This book is meant to bridge the gap between the rigorous mathematical treatment of external ballistics and the practical application of the subject. When I say ***practical,*** I'm talking about things that all shooters can understand and apply in order to achieve better performance. Some of the material is technical, but no more than it has to be.

The subject matter that fills these pages is inspired by years of experience and conversations with curious target shooters on the firing line and with long range hunters and tactical shooters. These are subjects that serious shooters care about and need to know in order to optimize the accuracy and precision of their shooting. I will try to avoid abstract, in depth explanations of things that won't help you shoot better! ***My objective is to help the average shooter improve their performance through a better understanding of the science behind shooting.***

For years I pondered the notion of writing a book about ballistics because it is a subject that I enjoy learning and writing about. I felt there was a great need for a book that could explain the science of external ballistics to average shooters in layman's terms. However, it's not enough to just re-word information that's already available. I didn't feel it was worth the effort unless I could make an original contribution to the subject. To this end, I set out to measure the true performance (Ballistic Coefficients) of modern rifle bullets. The first edition of this book was published in 2009 and contained measured BC data for just over 175 modern long range bullets. This library continued expanding as more bullets were tested, and when the second edition was released in 2011, it included data on 225 bullets. As even more bullets were tested, the library simply outgrew its original place as an appendix in this book and became its own book. In 2014, I published the first edition of *Ballistic Performance of Rifle Bullets* which contained live fire data on 400 modern bullets. As this library of bullet data continues to grow, future editions of *Ballistic Performance of Rifle Bullets* will be published to keep up with the new data.

Since the original library of bullet data was published as an appendix to the early editions of this book, there are numerous references to the ballistic performance data. As Chapter 2 will explain, the Ballistic Coefficient (BC) is the most important number for any kind of meaningful performance analysis including the calculation of accurate trajectories. A predicted trajectory is no more accurate than the information it's calculated with, and the BC is the input that characterizes the bullet. In the past, shooters have had to rely on the bullet manufacturer's advertised BC. For reasons that I'll explain later, the bullet manufacturers have historically advertised *inconsistent* and often *inaccurate* BCs. This situation has two major consequences. First of all, it prevents shooters from being able to make good comparisons of bullets from different makers. Secondly, shooters are unable to calculate the accurate trajectories that are required to hit targets at long range.

The accurate determination of a bullet's BC is not an easy task. The best way to determine BC is to instrument a range and perform carefully controlled test firings to *measure* the BC (vs predicting a BC with computer programs). This kind of testing is very expensive and complicated, but it's the only way to really know the BC of a bullet for sure. The book: *Ballistic Performance of Rifle Bullets* contains live fire test data on a growing list of bullets, and is the most extensive and accurate assembly of experimental BC data ever compiled. I consider the information compiled in that book to be my original contribution to the shooting sports.

The chapters that fill this book address various subjects of long range shooting, many of which have to do with accurate and meaningful calculation of ballistic trajectories. Regardless of what methods are used, a trajectory prediction can't be any more accurate than its least accurate input. I feel that traditionally, BC has been the input that's prone to the highest degree of error, so I believe this makes my compilation of experimentally determined BCs a valuable asset to the shooting sports.

The state of the art

There have been several important advances in the science of external ballistics that have yet to make it into mainstream practice. With this book, I intend to make these advances understood and available to all shooters.

The application of precision rifle fire at long range is a challenge comprised of many variables. Some of these variables are easy to measure and account for; others involve more guess work. The idea is to move the variables into the *known* category, and minimize the number and effect of the *unknowns*. One area that this book will transform into a known variable is trajectory calculations.

State of the art ballistics solutions have been available to the sporting arms industry for quite some time. We don't have to re-invent the wheel; shooters only need to learn how to effectively employ the tools that are already available. This book will walk the reader thru these details.

The intent of this book is not to advance the state of the art in exterior ballistics. The intent is to help the average shooter understand and take full advantage of the existing state of the art by using accurate data, and employing the most appropriate tools available to solve the problem. Before you start to think this sounds like a sales pitch, I won't push the sale of any specific software. In fact, the only software you need is included with this book, and is available free on the internet. I will simply focus on demonstrating how to use the tools in the best possible way.

Modeling

Not all parameters involved with external ballistics can be accurately measured. For these more subtle details, I rely heavily on a background in modeling and simulation to illustrate the physics of what's happening. They say a picture is worth a thousand words. Often times, a good model can be the picture that brings clarity to a situation. Digital computer models can be very misleading if the user doesn't understand their limitations. On the other hand, when models are used properly, they can be very powerful and educational tools.

Statistics

One problem with computer models and problem solutions in general is that they're inherently deterministic. In other words, if you feed it the same inputs, it will always return exactly the same outputs. Shooting, as we know, is not like that! Our objective as precision shooters is to minimize the uncertainties, and make our shooting system perform as consistently as possible. However, there will always be some degree of uncertainty to deal with. The good news is; we have the means to deal with the uncertainty involved in shooting, with statistics. Statistics is a very powerful, important and often misunderstood subject area for shooters. Shooting is full of measurable uncertainties (muzzle velocity, range, wind, powder charge, case weight, case neck thickness, bullet dimensions, etc.). It's obvious that the reason why shooters miss targets is entirely due to the uncertainties involved in shooting. ***Statistics is math's way of dealing with uncertainty.*** With just a few basic principles from statistics, shooters are empowered to make better informed decisions about their reloading and shooting. A systematic study of the uncertainties involved in shooting will be a common theme throughout this book. For many values that are given, the associated error bounds are given with them. Citing numbers in this way reflects the true non-deterministic nature of shooting. If I say the drop of some bullet is 55 inches, that number has value. But If I say the drop is 55 inches, +/- 5 inches based on the uncertainties involved, the shooter has better information to make a decision with.

The Big Picture

It's a good idea to take a step back once in a while and ask: ***What's the point?*** In this book, as we dive deep into the subjects within external ballistics, the big picture is always kept in the forefront. The material in this book is meant to help shooters achieve a deeper appreciation, understanding and enjoyment of shooting. Above all, the ***point is to achieve greater success!*** Whether you measure success in group size, points, or long range kills, the material in this book will help you do those things better.

Part 1: The Elements of Exterior Ballistics

Chapter 1: Fundamentals

There are many variables that come into play in long range shooting. To consider them all at once in their complexity would be overwhelming. In order to begin a systematic study of ballistics, we'll first break up the elements into 2 basic categories:

1. Deterministic variables
2. Non-deterministic variables

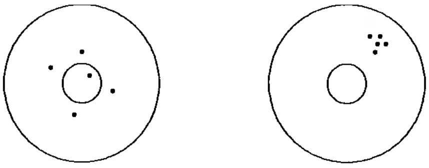
Deterministic variables are those variables that can be measured and accounted for. Most variables involved in long range shooting are deterministic. Gravity drop and spin drift are two examples of deterministic variables. Basically, deterministic variables are all those things that can be entered onto a predictive ballistics program and accounted for. If all the elements in long range shooting were related to *deterministic variables*, it would be quite easy to reliably hit targets at very long range. The most challenging elements of long range shooting are the *non-deterministic* variables.

Non-deterministic variables are those variables that cannot be directly measured, and affect the trajectory of the bullet. The most notorious and problematic non-deterministic variable in long range shooting is definitely the wind. Since the exact speed and direction of the wind cannot be determined at every point between the shooter and target, its effects cannot be precisely accounted for. Another non-deterministic variable is muzzle velocity variation. Ideally, every bullet leaves the rifle with the same muzzle velocity, and drops the same amount at a given range. The reality is that every shot leaves the barrel at a *different* velocity, and has a different amount of drop at long range. The goal is to hand-load ammunition that is as consistent as possible and produces the most uniform muzzle velocity, but there will always be some amount of *non-deterministic* variation. It's important to understand how to handle the uncertainties of shooting. Statistics is math's tool for doing just that.

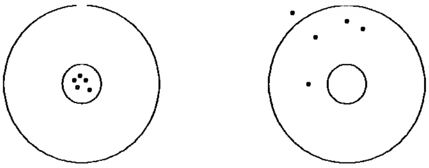
This book has chapters on each of the most important elements of long range shooting. It's important to categorize the elements as deterministic or non-deterministic so you know how to manage them. Getting control of the sights should be a deterministic variable. With careful attention to detail and quality components, there should be no excuse for missing a target because of a misunderstanding of the sights. The same goes for the rest of the deterministic variables. Everything affecting the flight of the bullet that can be measured should be measured and accounted for using predictive ballistics software. Chapter 8 will demonstrate the effective use of a ballistics program to account for all of the deterministic variables that affect a bullet on a long range trajectory. In reality, the only reasons (related to ballistics) for missing a target at long range are the non-deterministic variables. The non-deterministic variables are where you have to rely on statistics and imperfect human judgment. *After you have mastered the basic elements of long range shooting, the balance of your time spent training and improving will be with the non-deterministic variables.*

Accuracy and Precision

An important fundamental topic of shooting is accuracy vs. precision. In the context of shooting, accuracy is the measure of how close your shots are to the center of the target, and precision is how tightly the shots are grouped together (see Figure 1.1). It's important to distinguish between accuracy and precision because they're both important, but they're both influenced by different types of variables. For example, accuracy is more related to the elements involving the platform and the deterministic variables. For example, a problem with the sights will cause shots to miss the target *systematically*, meaning you may shoot a small group beside the intended point of impact.



Accurate but not precise **Precise but not accurate**



Accurate and precise **Neither accurate nor precise**

Figure 1.1. Examples of accuracy and precision.

In general, precision is determined by the non-deterministic variables. Group shooting (Benchrest competition) is only a contest of precision. It doesn't matter where the group is in relation to the center of the target; all that matters is how close the shots are to each other. Score shooting requires both accuracy and precision. The shots must hit near the center of the target *and* be tightly grouped to maximize score. Long range hunting and sniping also requires both accuracy and precision.

Understanding the Shooting Objective

Serious shooters know how to consider the objective of their shooting. For example, if the shooting is being done on paper targets, then bullet impact energy is a non-issue. If the shooting is being done in uncertain wind conditions, then minimizing wind drift is paramount. Here's an example to illustrate the point. Consider a varmint hunter who has hunted groundhogs for many years without a rangefinder. This hunter favors cartridges like the .22-250 and .220 Swift because of the very flat trajectories. A flat trajectory is an asset to a shooter who has to deal with range uncertainty. Now, give this guy a laser rangefinder and you've changed the nature of his shooting. By removing the range uncertainty, a flat trajectory is no longer a valuable asset. Now the biggest uncertainty is wind deflection, and wind deflection is minimized by a different type of shooting system than the *flat* shooting system. ***Selecting the proper shooting equipment is about minimizing the biggest sources of uncertainty.***

As long as the shooting objective is narrow and well defined as in target shooting, the task is easy. The challenge comes when you want to use one rifle for multiple objectives. When that's the case, some compromise is usually in order.

Understanding Measures of Ballistic Merit

Once the shooting objective is clearly defined, the next step is to consider the *measures of ballistic merit* that are relevant to the objective. A *measure of ballistic merit* is basically anything that relates to ballistic performance. The following subsections define some common measures of ballistic merit that are used to analyze the performance of shooting systems.

Muzzle velocity

For any bullet of any caliber, weight, and BC, elevated muzzle velocity will enhance all measures of external ballistic performance. Bear in mind that excessive muzzle velocity can have adverse effects on precision, accuracy and safety if taken to the extreme.

Muzzle velocity is typically measured in feet per second (fps) by shooting thru/over a chronograph. In addition to knowing the average muzzle velocity, shooters need to know and manage the variation in muzzle velocity for the shooting system under evaluation. The variation or uncertainty in muzzle velocity is typically quantified by two statistical parameters: Standard Deviation (SD) and/or Extreme Spread (ES). These statistical measures will be better defined in a later section. For now, the point is to understand the importance of measuring the average muzzle velocity, as well as the variation in muzzle velocity.

Ballistic Coefficient

In words, the Ballistic Coefficient (BC) determines how well a bullet can maintain velocity. Bullets with high BCs maintain velocity better. For long range small arms fire, downrange ballistic performance is largely dependent on how much velocity is retained by the bullet, which makes BC a very important measure of ballistic merit. BC will be the subject of much more discussion in this book.

Trajectory

As illustrated in the previous section about the shooting objective, there is great value in a flat trajectory for applications where range uncertainty exists. Small caliber rifles that fire light weight bullets at very high muzzle velocities (like the .22-250 and .220 swift) have the flattest short range trajectories. However, as Chapter 3 will demonstrate, a larger caliber, heavier bullet with a higher BC and slower muzzle velocity can have a superior (flatter) trajectory far downrange. For this measure of ballistic merit, superiority is determined by *danger space.* Danger space is similar to point blank range. The bigger the danger space is, the greater the chance of hitting a target, given a range or muzzle velocity uncertainty. Point blank range and danger space will be more completely explored in Chapter 3. For now, it's only important to get familiar with the concept of trajectory as a measure of ballistic merit that's related to range uncertainty.

Wind Deflection

Next to range uncertainty, wind uncertainty is usually the biggest problem to overcome for most long range shooting applications. All of Chapter 5 is devoted to the mechanics of wind deflection. The main idea to come to grips with is that the exact speed and direction of wind between the shooter and target in the field cannot be exactly measured and corrected for. We try to quantify wind the best we can, but in the end, there will always be some uncertainty. The shooting system that's best at hitting targets in the wind is the one that minimizes the magnitude, and with it, the uncertainty of wind deflection. For example, consider two rifles. Rifle A has 100" of wind drift at 1000 yards in a 10 MPH crosswind, and rifle B has 50" of wind drift in the same condition. If the wind speed changes or is misjudged by 2 MPH, rifle A misses the point of aim by 20", while rifle B only misses by 10". *The same wind uncertainty results in less miss distance for the bullet that has less wind deflection.* This principal applies to every long range shooting discipline. It doesn't matter if you'll only get one long shot at an elk, or if you're in the middle of a 20 shot string of target shooting and your last shot was 30 seconds ago. The less wind drift a bullet has, the less miss distance is incurred by uncertainties in the wind speed and direction. The fundamental measure of ballistic merit that quantifies wind deflection is *lag time.* Lag time is determined by a bullet's BC and muzzle velocity, and will be thoroughly explored in Chapter 5.

Kinetic Energy

Kinetic Energy (KE) is the measure of striking energy a bullet has as it travels downrange. KE is measured in foot-pounds, and is only relevant for certain applications where the shooter cares about the bullet's affect on the target. Hunting, military and law enforcement applications come to mind. Target shooters don't care about how much KE their bullets have, just so it's enough to put a hole in the paper. Also, varmint hunters usually aren't concerned with KE either, because most center fire rifles, even down to .17 caliber, are lethal enough to kill vermin.

KE is proportional to the bullet's mass and velocity. A common way to use KE is to determine how much KE is required to accomplish the shooting objective (humane kill of an animal or destruction of some material) and then calculate the range that the bullet falls below the required threshhold. For example, let's say it takes 1,000 foot-pounds of KE to humanely kill a white tailed deer with a .30 caliber 165 grain Sierra Game King bullet. A .308 Winchester that can shoot the 165 grain bullet at 2700 fps has 2600 foot-pounds of KE at the muzzle, and drops below 1000 foot-pounds somewhere around 600 yards. Based on this measure of ballistic merit, we can say that the .308 loaded with 165 grain Game King bullets is *effective* on white tailed deer out to 600 yards. The actual effective range may be less if the accuracy of the rifle or other field variables prevents reliable hits at that range.

Measures of merit not related to external ballistics

It's important to realize that there are many variables related to long range shooting that are outside the scope of external ballistics and this book. Terminal bullet performance, quality of optics, the physical size of the rifle, shooting skills, and range estimation are all important factors that are not given much consideration in this book, but are very important aspects of shooting. In other words, your choice of equipment shouldn't be made completely on ballistics alone, but ballistics is an important consideration. *The intent of this book is to help shooters understand ballistics so they can make decisions that are best for their application.*

The remaining Chapters in Part 1 of this book discuss the details and science of the important elements in external ballistics. Specifically, the most important forces that govern the flight dynamics of projectiles like gravity drop and wind drift are addressed. Part 2 is a collection of specific and general analysis for various types of target shooting and hunting applications. The idea is to provide the reader with enough fundamental information in Part 1, so they can perform the detailed and meaningful analysis as presented in Part 2. Part 3 presents the properties of long range bullets. This information is intended to give the reader a feel for the important features of the modern long range bullet in terms of design, materials, and performance.

Chapter 2: The Ballistic Coefficient

The Ballistic Coefficient (BC) is the most widely recognized and important measure of a bullets exterior ballistic performance. Knowing the BC of a bullet allows shooters to calculate trajectories and do various types of downrange performance analysis. Since the BC is so important, the bullet manufacturers advertise BCs for their bullets on the boxes, in reloading manuals, or on the company's website. For various reasons, the advertised BCs are usually inaccurate to some degree. That error translates into error and doubt in any ballistic performance analysis done using that BC. *Knowing an accurate BC is critically important for conducting meaningful exterior ballistic analysis and choosing the right bullet for the application.*

This chapter explains what the ballistic coefficient is, and how to use the information to be more successful at long range shooting.

What is the Ballistic Coefficient?

There are some fundamentals from *aerodynamics 101* that are required to understand external ballistics. I've included the equations for those readers who want to understand and exercise the math, but I've done my best to present the important ideas in a conversational format. In other words, ***you don't have to understand the equations in order to understand the ideas***.

In words, the ballistic coefficient is a measure of how well a bullet *penetrates the air*. The attributes of a bullet that will determine how well it penetrates the air are: weight, cross-sectional area, and form factor. The weight is obvious; the heavier a bullet is the better it can penetrate the air. Cross sectional area is obvious as well. The narrower a bullet is the better it will penetrate the air. The form factor is a measure of how streamlined the bullet is. The following equation shows how the bullet's parameters determine its BC:

$$BC = \frac{W/7000}{cal^2 \cdot i} \quad \left(\frac{lb}{in^2}\right)$$

Equation 2.1

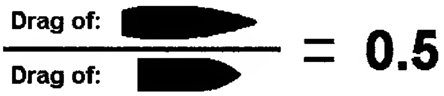
Where:

BC is the ballistic coefficient in lb/in^2
W is the bullet weight in grains
cal is the bullet caliber in inches
i is the bullet's form factor and has no units

BC has units of *pounds per square inch,* even though the units are usually ignored. The weight and caliber of the bullet are easy to determine, so the only component of the BC equation that's a question is the form factor.

What is Form Factor?

The form factor is a multiple that compares a bullet's unique drag to that of a *standard* bullet. As it is drag-based, a high value means the bullet is less aerodynamically efficient than the *standard bullet* and conversely, a low form factor represents an efficient shape that has less drag in flight. The following is a visual representation of a form factor.



Equation 2.2[1]

In words, this representation says that the more streamlined bullet on top has ½ the drag of the bullet on the bottom at a given flight speed. This example uses 0.5 but the form factor can be any number, usually ranging from 0.45 to 0.6. It may be hard to believe that the two shapes could have such a big difference in drag, but at high supersonic speed, the cost of a blunt nose and flat base are much greater than at low, subsonic speeds that we're directly familiar with. The projectile on the bottom is the *G1standard projectile.* Traditionally in the sporting arms industry, all of our BCs are based on form factors related to the G1 standard. There are other, more appropriate standards for long range bullets that will be discussed shortly.

In order to actually calculate a form factor and ballistic coefficient, you need to know the *drag coefficient* of the bullet at a given speed so you can compare it to the drag coefficient of the G1 standard and get the form factor. The drag coefficient is a dimensionless quantity that has to do with how much drag the bullet will have at a given speed. More streamlined shapes have lower drag coefficients and at supersonic speeds, the drag coefficient changes a lot with velocity. Figure 2.1 shows the *drag curve* for a typical long range bullet.

---

[1] A more technically thorough definition of form factor is given in the Appendix.

As indicated in Figure 2.1, a typical long range bullet fired at a muzzle velocity of 3000 fps has a drag coefficient of about 0.25 at that speed. As the bullet slows down, the *drag coefficient* increases until it slows to subsonic speed (below 1120 fps in standard conditions) then it drops abruptly. Remember that even though the *drag coefficient* of the bullet increases as the bullet slows down, the actual force of drag (measured in pounds) decreases because of the decreasing flight speed.

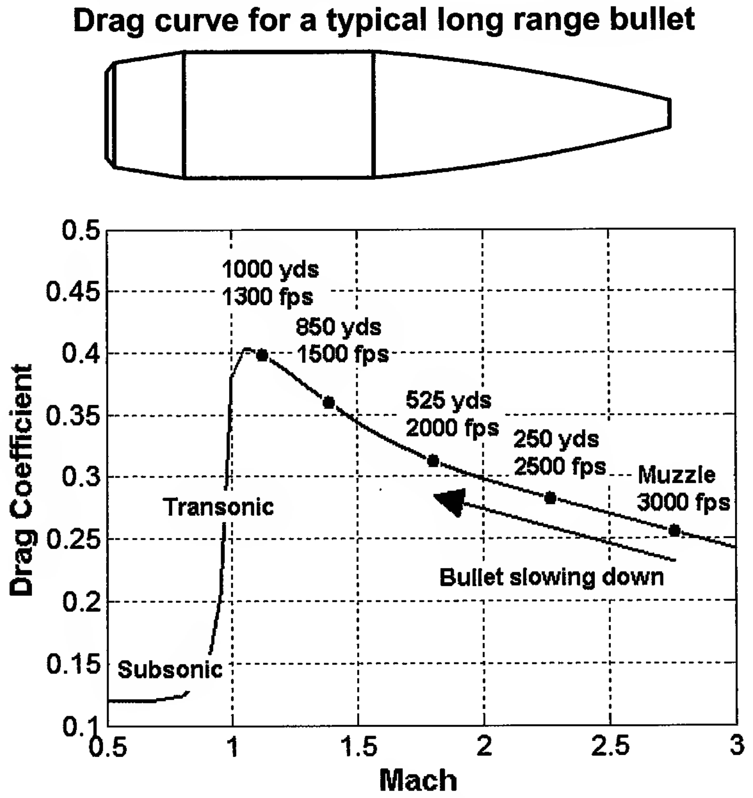


Figure 2.1. This plot shows the drag curve for a typical long range bullet.

Let's do an example calculation of BC for the typical long range bullet above that has a drag coefficient of 0.25 at 3000 fps. At 3000 fps, the *G1 standard projectile* has a drag coefficient of about 0.52. So the form factor for a typical long range bullet is: 0.25/0.52 = 0.48 in this example. Note this form factor doesn't depend on caliber or weight, just drag coefficient. In order to calculate the bullet's BC, apply Equation 2.1 with the form factor of 0.48. The following calculation is for a 155 grain .308 caliber bullet:

$$BC = \frac{155/7000}{.308^2 \cdot 0.48} \left(\frac{lb}{in^2}\right) = 0.486 \left(\frac{lb}{in^2}\right)$$

The units (lb/in^2) are usually dropped or ignored, but are included here to remind the reader of their existence.

This BC is only valid for the speed it was calculated at; ie 3000 fps. If you considered the form factor and BC at a different speed, they would be different because *the drag coefficients of bullets are different at all speeds.* Figure 2.2 shows the drag coefficient of the G1 standard compared to the typical long range bullet from 0 fps to 3300 fps. Notice how much higher the drag coefficient is for the high drag G1 standard projectile. At 3000 fps, the form factor was 0.48, but at another speed, the form factor will be different. For example, at 1500 fps, the drag coefficient of the typical long range bullet is 0.37 and the drag coefficient of the G1 standard projectile is 0.66. This produces a form factor of 0.56. Therefore, the BC at 1500 fps for the same 155 grain .308 caliber bullet is:

$$BC = \frac{155/7000}{.308^2 \cdot 0.56} \left(\frac{lb}{in^2}\right) = 0.417 \left(\frac{lb}{in^2}\right)$$

This variation in form factor is the reason why BC changes with velocity. Many shooters are aware that a bullet's BC is higher at higher speeds, but don't know why. It's all based on how the drag of the bullet compares to the drag of the G1 standard projectile. If a BC is calculated for a bullet at a particular speed and that BC is used in a ballistics program, most programs will apply the same BC at all speeds, and the output will be in error because *the drag of the actual bullet changes with speed differently than the G1 standard bullet's drag changes with speed.*

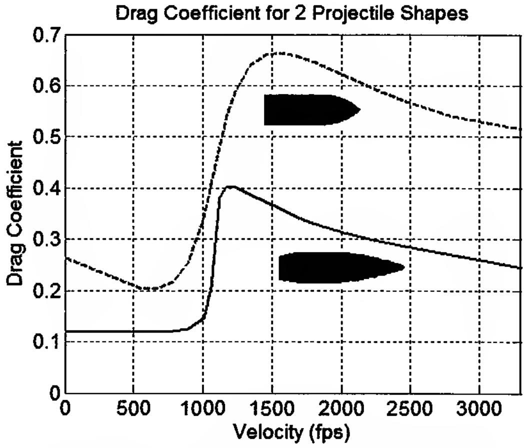
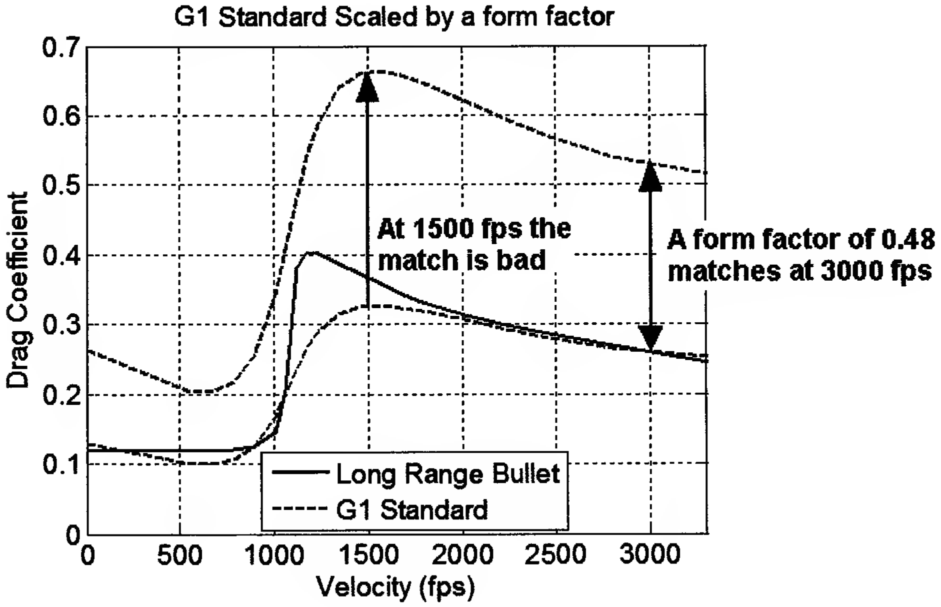


Figure 2.2. The dotted line represents the high drag of the G1 standard projectile (top). The bottom line is the lower drag of a modern long range bullet.

Figure 2.2 is a visual depiction of the mismatch in drag between the G1 standard projectile and a typical long range bullet. You can see that the form factor can be established for some speed (in this case 3000 fps), and an accurate BC calculated at that speed. However, since the drag curves are different shapes, the typical long range bullet requires a different form factor as the bullet slows down.



At 1500 fps the match is bad

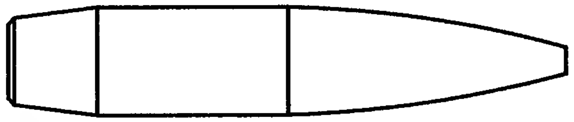
A form factor of 0.48 matches at 3000 fps

Figure 2.3. The form factor required to make the G1 drag match the real drag is different at all speeds.

From about 2000 fps and faster, the drag curve of the typical long range bullet and the G1 standard do not change very much. As a result, BCs are fairly consistent for these high speeds. However, as the bullet slows below 2000 fps, the difference in the shape of the drag curves becomes increasingly large. If it's not corrected, this mismatch in the shape of the drag curves can cause serious inaccuracies in the output of ballistics programs that accept a single BC input. *The biggest challenge of using ballistic coefficients effectively is managing the velocity dependence.*

In order to address the issue of BCs changing with velocity, Sierra Bullets presents the BC of their bullets in velocity segments. For example, Sierra presents the BC of its 6.5mm 142 grain Match King bullet as shown in Figure 2.4.

Sierra 6.5mm 142 grain Match King



Sierra's advertised Ballistic Coefficient:

0.595 at 2800 fps and above
0.580 between 2850 fps and 2400 fps
0.575 between 2400 fps and 2050 fps
0.550 at 2050 fps and below

Figure 2.4. The velocity banded BC of Sierra Bullets.

Sierra's ballistic coefficients are established experimentally. In other words, the BCs are direct measurements as opposed to computer predictions. I bring this up to make the point that the change in BC with velocity is real, and is not an artifact of inexact math. The different ballistic coefficients that are measured for Sierra bullets at different speeds translate to specific form factors which effectively describe a drag curve that's shaped differently than the G1 standard. Figure 2.5 shows the shape of the bullet's drag curve that is implied by multiple BCs.

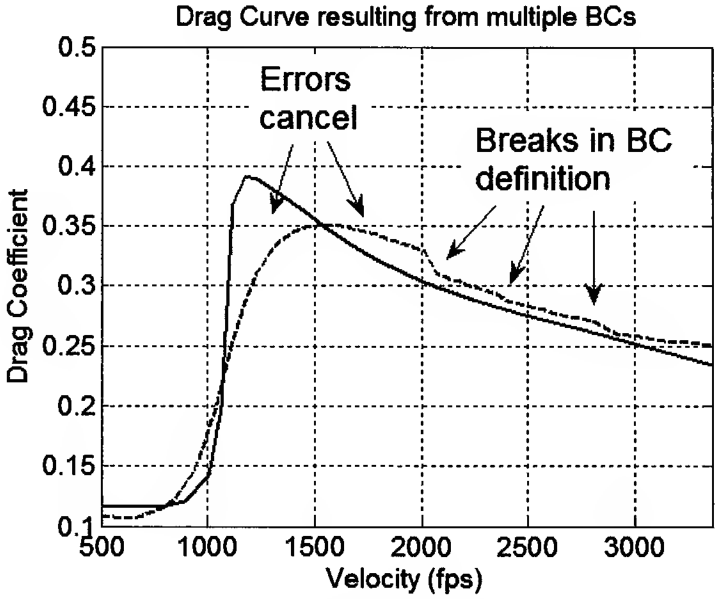


Figure 2.5.The dotted line is the drag curve that's implied by the multiple BCs advertised by Sierra for the 142 grain Match King. The solid line is the actual drag curve of this bullet.

Using multiple BCs, you can produce a drag curve that's a better match to the drag of the typical long range bullet. You can see where the G1 drag curve is *adjusted* by the different BCs. Between 2000 and 1500 fps, the drag will be modeled a bit high by the G1 curve, but below 1500 fps, the two curves cross, somewhat offsetting the first error caused by the mismatching drag curve.

Another way to mitigate the effects of mismatching drag curves and the velocity dependence of BC is to use a BC that's averaged for a wide range of speed that's typical of long range shots. For example, Figure 2.6 shows how the drag curves compare for a bullet that's using a BC that's averaged between 3000 fps and 1500 fps. From 2000 fps and up, the drag represented by the average G1 BC is just a little higher than the drag of the actual bullet. Below 2000 fps, the error quickly grows, but isn't as bad as it would have been, had the BC been based on high velocity flight alone.

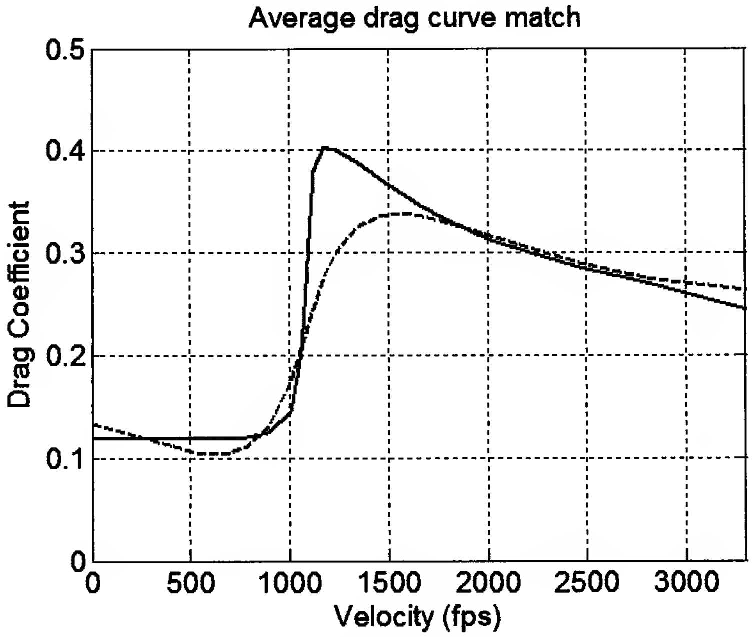


Figure 2.6. Representing the average drag of a long range bullet using a constant G1 form factor. The dotted line is the G1 representation of the long range bullet (solid line).

So there are several approaches to managing the velocity dependence of BC. Some are more accurate, some more convenient. The commonly used trick of simply stating the high velocity BC allows bullet makers to represent their product in a favorable way without being *technically* inaccurate. After all, the BC is valid, if only for high speed. Advertising high velocity BCs isn't necessarily done to mislead would-be customers. Some manufacturer's test facilities only allow measurement over short ranges (100 yards). The result is they end up producing a BC that's based on high velocity flight. This is not dishonest, but if a shooter uses that G1 BC which is based on short range (high velocity) testing only, he can expect major errors in his predicted trajectory at long range when the bullet slows down. In other words, *your bullet won't hit where your ballistics program predicts it will hit.*

Using BCs that are defined in segments addresses the velocity problem by adjusting the BC for each segment of flight speed. This approach can be more accurate than using a single BC because it allows you to effectively *force* the drag to be modeled as it was measured. However, it's still very difficult to achieve a good match below 1500 fps and the results represent a balancing act of offsetting errors as shown in Figure 2.5. Another practical pitfall of the *velocity banded BC* approach is that many novice shooters don't understand why there are multiple BCs, so they don't know which one to choose. A common misconception is that the velocity bands are based on *muzzle velocity*, and the high speed BC *alone* is mistakenly used for analysis as a result. Said another way, shooters that use only the highest value of a velocity banded BC will suffer the same inaccuracy as the above case (where the BC is based on high velocity only).

One last problem with the multiple BC approach is that many ballistics programs don't allow the input of multiple BCs. If you have a ballistics program that only accepts one BC and you're modeling a *velocity banded BC,* the correct approach is to average the velocity banded BC for the range of flight speeds you're interested in, and enter that single value into the program. Then there's the plain mathematical irony of using multiple BCs. The whole point of using a form factor is to relate the drag of a bullet to a *representative standard* so that the bullet's drag can be accurately accounted for at all speeds with one number. Choosing a *non-representative standard* to define a form factor and BC defeats the very purpose of using BCs in the first place.

The many errors, pitfalls, misunderstandings and inaccuracies of BCs are mostly all due to the complications of velocity dependence which exists because the G1 standard is not representative of typical long range bullets. *All of these problems can be solved by choosing a more representative standard projectile on which to base form factors and BC's.* In the remainder of this chapter, I'll be presenting such an alternative standard. Remember, this is not a big change to how we do things now; it's not advancing the state of the art, it's simply a better way to use the existing state of the art.

A better standard projectile for long range bullets

The stated objective of this book is to present information on exterior ballistics that shooters can use to achieve greater success at long range shooting. The challenges presented by velocity dependent BCs offers a great opportunity to solve a problem by presenting a better alternative.

So far the discussion of ballistic coefficient has mostly been an exploration of the velocity dependence of BC. We've talked about where the velocity dependence comes from (G1), its effects, and various options for managing the resulting problem. This is important because the value of a bullet's ballistic coefficient is such a critical number for long range shooters. The uncertainty and the *smoke and mirrors* of velocity effects surrounding the classical G1 referenced BC are to blame for so many misconceptions, inaccurate conclusions and poor decisions made in long range shooting. There is a better way. It's not hard, and it's not advancement in the *state of the art.* The current state of the art is quite sufficient for our purposes as long range shooters. *What I wish to present is simply the best way to use the current state of the art.*

Recall the definition of form factor - a multiple that relates the drag of a bullet to that of a standard bullet such as the G1 standard already discussed. Due to the mismatch between typical long range bullets and the commonly used G1 standard, the form factor varies according to velocity which in turn causes the BC to constantly change both with muzzle velocity, then as the bullet slows down during its flight. *There are other standard projectile models besides the G1 which represent different shapes.* The *G7 standard* *projectile* has a shape very similar to that of modern long range bullets. Unlike the short nosed, flat based G1 standard, the G7 standard has a long pointed nose and a boat tail.

The best way to solve the problem of velocity dependant form factors and BCs is to base the BC on a more representative standard projectile. Figure 2.7 shows the G1 and G7 standard projectiles. It's obvious which of the two standards is most representative of modern long range bullets.

As a consequence of the G7 standard projectile being shaped more like a modern long range bullet, its drag curve is very similar to that of a modern long range bullet. *Because the G7 standard projectile is such a close match to modern long range bullets, a form factor based on the G7 standard is very constant, and doesn't change much with velocity.* As an example, consider the gray line in Figure 2.7 that gray line represents the drag curve of a modern long range bullet. There's only a very small difference between the drag of the modern long range bullet and the G7 standard. As a result, the modern long range bullet will have a form factor that's very close to 1.0, and is very constant for a wide range of velocity including transonic and subsonic.

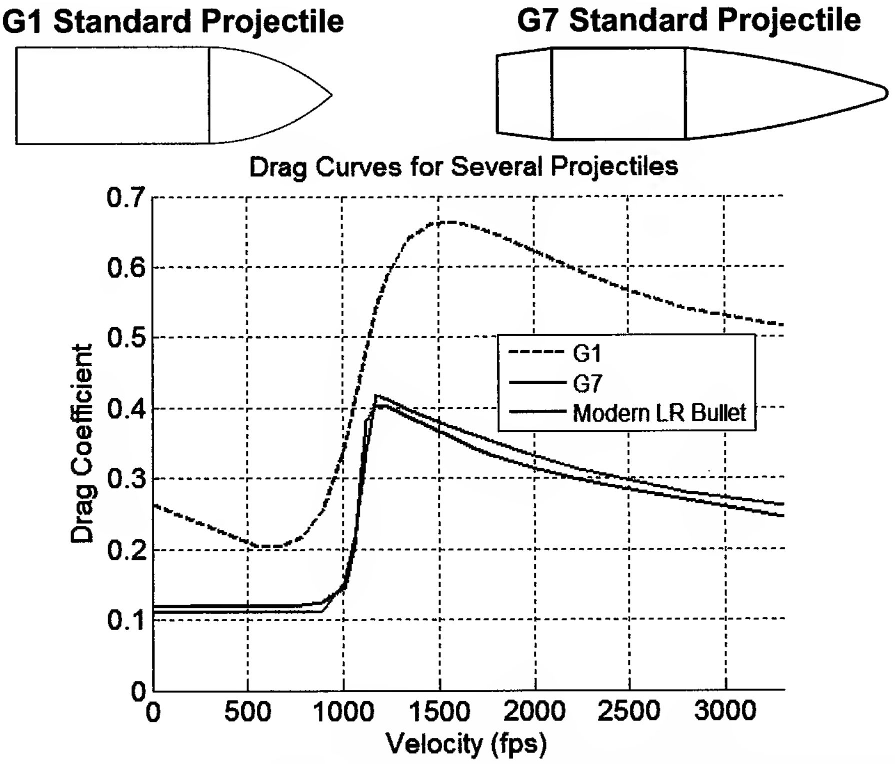


Figure 2.7. Drag curves of the G1 standard projectile compared to the G7 standard projectile. The low drag G7 standard is much closer to the drag of modern long range bullets.

Notice how much lower the drag curve is for the more streamlined G7 projectile compared to the G1. This is showing that at the same speed, the G1 projectile has almost twice the drag of the G7. In addition to the gross offset in drag, the shapes of the drag curves (velocity dependence) for the two projectiles are quite different as well, especially below 2000 fps.

Figure 2.8 shows some measured drag data for the 6mm 90 grain Lapua Scenar bullet. The data points scattered on the plot are the result of test firing and measuring the bullets actual drag, a process that will be discussed later in this chapter.

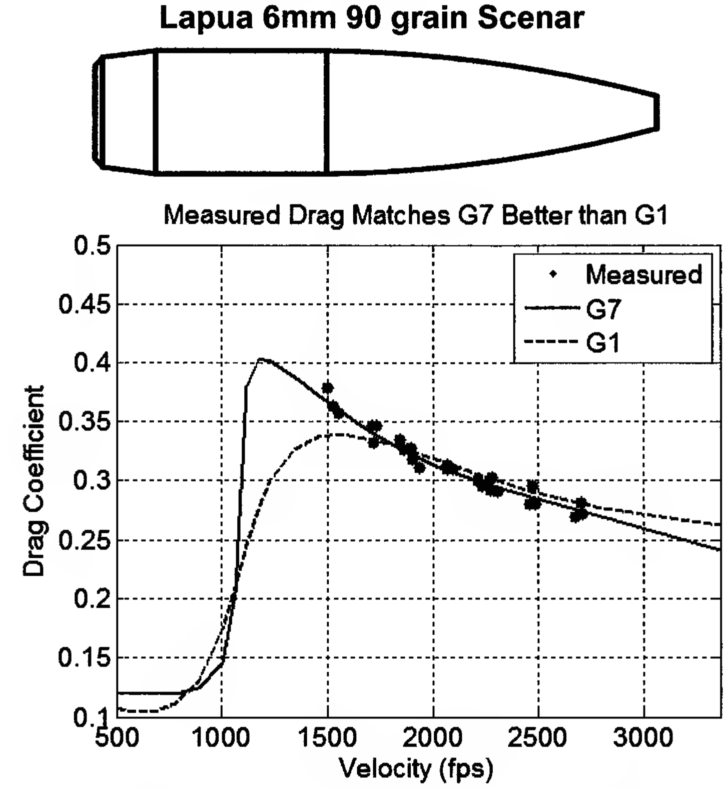


Figure 2.8. Measured drag of a typical long range bullet.

Here the G1 drag curve (dotted line) is scaled by a form factor of around 0.5 to bring it down into better alignment with the measured drag of this bullet. The scatter of the measured data points about the average drag curve is normal. *The point is that the measured drag points follow the G7 drag curve closer than the G1 drag curve.* This should come as no surprise, since this bullet is much more similar in shape to the G7 standard projectile than the G1 standard projectile. For the Lapua 6mm 90 grain Scenar, the measured G1 form factor ranges from 0.489 to 0.551, which is a span of about 12% variation. If you define the form factor in relation to the G7 standard instead, the form factor ranges from 0.991 to 1.009, a range of less than 2% variation. We can draw two important conclusions from the above statements:

- The fact that the G7 form factor is close to 1.0 means that the drag of the bullet is close to the drag of the G7 standard.

- Because the shapes of the two bullets (the Lapua and the G7 standard) are very similar, they can be expected to have similarly shaped drag curves, which results in BCs that don't change with velocity.

The most important conclusion is:

The form factor and BC of a typical long range bullet display much less velocity variation when based on the G7 standard as opposed to the G1 standard.

You can be assured that the Lapua 6mm 90 grain Scenar has a drag curve that is truly representative of modern long range bullets. Also, the drag curve implied by Sierra's velocity banded BCs indicates a similarly shaped drag curve for the 6.5mm 142 grain Match King. Later on in this Chapter, I'll present some Doppler radar test results acquired by Lapua. Doppler radar measurement is the undisputed Cadillac of credibility for measuring bullet performance and the results show very clearly that the supersonic drag curve of typical long range bullets is a better match to the G7 standard than the G1 standard. I'm highlighting the experimental results to make it clear that the supersonic drag curve profile isn't just some artificial *trickery* of some kind, but is the genuine reality of supersonic drag.

The approach that I recommend for long range bullet BCs is to reference them to the G7 standard instead of the non-representative G1. Doing this solves the problem of velocity dependence and produces more accurate trajectory predictions and more meaningful performance comparisons. Using G7 BCs is easier than it might seem, but there are some challenges.

First of all, switching standards from G1 to G7 means that the numeric value of the BC will be different. For example, a bullet that has a G1 BC of 0.500 will have a G7 BC that's closer to 0.260. The bullet is obviously the same, but if you define its form factor using a different standard, its value will be different. This means that G7 BCs will be *unfamiliar* until you get used to them. BCs have been referenced exclusively to the G1 standard for so long, and that's just what we're used to. What I'm saying is that it will take some time to get used to BCs based on a different standard.

The second challenge is that many ballistics programs will only accept G1 based BCs. If you enter a G7 BC into a ballistics program without indicating it's a G7 BC, the program will simply treat it as a G1 BC and the results will be way off. The program has to be able to make proper use of G7 BCs. The ballistics software program that's included with this book will help to alleviate that problem, as it allows you to use BCs referenced to either the G1 or G7 standard.

The third significant challenge of adopting the new standard is that many bullet manufacturers don't currently provide G7 BCs for their bullets. This problem is addressed in *Ballistic Performance of Rifle Bullets;* a book that contains experimentally measured BCs referenced to both G1 and G7 standards for hundreds of modern long range bullets. The appendix of this book contains a table of BC's for the 533 bullets that have been tested as of 2015, and matches up with the library contained in the second edition of *Ballistic Performance of Rifle Bullets.*

By using accurately measured BCs referenced to a representative standard along with the software required to use them, you are empowered to model long range trajectories that are far more accurate than you can generate with the non-representative G1 BCs and their velocity dependence problems.

Let's look at some examples of the errors that occur by using G1 BCs.

Example 2.1

In this example, we'll look at the Lapua 6mm 90 grain Scenar that was presented earlier. I chose this bullet because there are several sources of experimental data that are in agreement with each other as well as conforming well to the G7 standard drag curve. For these reasons, we can consider the trajectory predictions using a G7 BC to be *truth* data. We'll compare the truth data to the predictions based on several representations of the G1 BC.

The first step is to calculate the two types of BCs using the bullet's weight, caliber and form factor. The average G7 form factor for this bullet is 0.999, and the G7 referenced ballistic coefficient is:

$$BC_7 = \frac{90/7000}{.243^2 \cdot 0.999} \left(\frac{lb}{in^2}\right) = 0.218 \left(\frac{lb}{in^2}\right)$$

The subscript *7* on the BC above indicates a BC that's referenced to the G7 standard.

Now we'll calculate two BCs based on the G1 standard. The first one will be based on high speed (3000 fps), and the second based on average speed between 3000 fps and 1500 fps. The measured G1 form factor of this bullet at 3000 fps is 0.489, so the G1 BC at 3000 fps is:

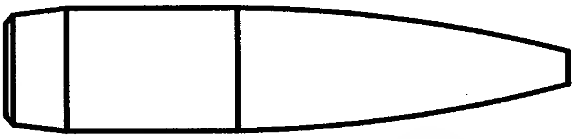
$$BC_1 = \frac{90/7000}{.243^2 \cdot 0.489} \left(\frac{lb}{in^2}\right) = 0.445 \left(\frac{lb}{in^2}\right)$$

Now let's calculate the average G1 BC for this bullet between 3000 fps and 1500 fps. The average G1 form factor is 0.512, so the average G1 BC is:

$$BC_1 = \frac{90/7000}{.243^2 \cdot 0.512} \left(\frac{lb}{in^2}\right) = 0.425 \left(\frac{lb}{in^2}\right)$$

Figure 2.9 shows the results of a trajectory prediction using the BCs we've just calculated.

Lapua 6mm 90 grain Scenar



	G7 BC	High speed G1 BC	Average G1 BC
BC value	0.218	0.445	0.425
Predicted drop	-333"	-325"	-338"
Predicted velocity	1190 fps	1276 fps	1227 fps

Figure 2.9. Trajectory predictions at 1000 yards resulting from different types of BCs. The drop is calculated based on a 100 yard zero.

For the G1 BC that's based on high speed, there is an error of -8" in the predicted drop of the bullet at 1000 yards and +86 fps error in remaining velocity compared to the prediction made from the G7 BC. The error in the remaining velocity prediction is important for long range shooters because you have to know at what range the bullet goes transonic (about 1200 fps; more discussion on this subject in Chapter 10). The G7 BC predicts much less remaining velocity than the G1 BC. According to the G1 prediction, it appears the bullet is reaching 1000 yards with plenty of speed, when in reality its arrival speed is much less than comfortable. Now consider the trajectory prediction based on the average G1 BC. This prediction has +5" of trajectory error and +37 fps of velocity error. The error is less than for the high velocity G1 BC, but it's error that's completely avoidable by using the G7 BC.

One thing to point out about using G7 form factors that are close to 1.0 is that they result in BCs that are close to the bullets *sectional density*. Sectional density is equal to the bullets weight (in pounds) divided by its caliber squared. In other words, the sectional density is the BC *without* the form factor. The sectional density of a bullet is often thought of as the bullet's potential to *penetrate its target.* It's convenient that dividing the sectional density by the bullets drag form factor results in the *BC* of the bullet, which is the measure of how well the bullet *penetrates the air.* Bullets that are shaped similarly to the G7 standard will have a form factor close to 1.0, which means they will have a G7 BC that's close to their sectional densities. Bullets with *higher drag* than the G7 standard will have a form factor *greater than 1.0*, and their G7 BCs will be *lower than their sectional densities.* Likewise, bullets with *less drag* than the G7 standard will have form factors *less than 1.0* and G7 BCs that are *higher than their sectional densities.* The 90 grain Lapua Scenar used in this example has a form factor that's very close to 1.000 (it's actually 0.999). The bullets sectional density is:

$$SD = \frac{90/7000}{.243^2} \left(\frac{lb}{in^2}\right) = 0.218 \left(\frac{lb}{in^2}\right)$$

You can get the G7 BC easily from the sectional density simply by dividing sectional density by the G7 form factor:

$$BC_7 = \frac{SD}{0.999} \left(\frac{lb}{in^2}\right) = 0.218 \left(\frac{lb}{in^2}\right)$$

In this case, the bullet's form factor is so close to 1.000 that the sectional density and BC are equal within round off error.

The preceding example illustrated the error you can expect to incur by using BCs referenced to the wrong standard. Even greater error is introduced by using BCs that are based on the wrong standard *and* inaccurate. For example, the G1 BCs for the 6mm Lapua Scenar in the previous example were at least based on accurately measured data. However, some bullet companies advertise G1 BCs that have not been measured accurately (or even measured at all), and as a result are neither accurate nor consistent with each other. In other words, the experimental BC data published in *Ballistic Performance of Rifle Bullets* solves two problems:

- First, the BCs are referenced to the G7 standard which solves the velocity variation problem, and
- The BCs were all measured using identical methodology, one that's produced results within +/- 1% of each other on re-running tests.

Comparing my measured test results to the manufacturers' advertised BCs revealed a wide range of error, some as large as 15% or more in both directions. As a shooter, it's very challenging to predict a useful trajectory using G1 BCs that suffer from velocity variation *and* are also inaccurate. This leads into the next section of this chapter which describes how the BCs in *Ballistic Performance of Rifle Bullets* were measured.

Measuring Ballistic Coefficient

Since BC is such an important and fundamental measure of ballistic performance, there ought to be some standard test for determining it, right? In fact, the methods for experimentally determining BC are as various as the resources and whims of the different bullet companies. Just for completeness, I'll briefly describe some of the more common ways that one can experimentally determine BC.

Probably the simplest way to derive a BC is to go by the observed drop of the bullet at various ranges. If you measure: muzzle velocity, range to target, atmosphere, and have a known zero at some range, you can (in theory) determine the BC of the bullet based on its drop. As with many things, the simplest way stands to be the least accurate. ***The biggest problem with this approach is the rifles ability to group precisely.*** For example, if you're measuring the drop over 600 yards, there's about 0.4" difference in drop for every 1% difference in BC. In other words, if you can't resolve the *true center of your group* within +/- 0.4" at 600 yards (which is extremely unlikely) you can't measure BC within +/- 1% based on drop. This same logic applies at any range, and is the biggest show stopper with this method. Of course you can approximate BC, but the bullet makers already give us approximate values. If you're after precise BC measurement, you would have to go to incredible lengths to minimize uncertainties and get the BC based on observed drop.

The most obvious and popular way to measure BC is by shooting over two chronographs placed at a known distance away from each other. If done correctly and carefully, this method has a high chance of producing accurate and precise results. The biggest problem with this method is practicality. What I mean is that an error analysis reveals that the chronographs should be placed as far apart as possible. In this way, the actual velocity decay of the bullet is large compared to the resolution of the chronographs. For example, placing the chronographs 50 yards apart wouldn't work very well because the bullet only loses about 100 fps in 50 yards. If the chronographs are only accurate to within +/- 5 fps, then you will have a lot of error in the BC measurement.

In order to drive the uncertainty down, you have to put a lot of distance between the chronographs so the velocity decay of the bullet is relatively large compared to the likely chronograph error. By placing them 300 yards apart, you'll be dealing with around 450 fps of velocity decay, and still have the same +/- 5 fps uncertainty in the chronograph readings. This would give acceptable results. However, the practical problem of this approach is that ***sooner or later, you're going to nail that downrange chronograph***, especially if you want to test a lot of different bullets. You might have the accuracy to *thread the needle* with your favorite target load, but what if you want to test 10 different bullets, all having different muzzle velocities and zeros? It becomes an incredible challenge to place every shot thru the window of the chronographs optic sensors. Of course, there is the option of constructing larger chronograph sensors that use non-optical sensors. Several people have used this method successfully to capture velocities at long range in the past. Done properly, this method can be very successful. Refer to following discussion on the Phoenix Test about velocity derived BC's for the Australian made .30 cal 155 HBC bullet.

When the Government/military needs to measure the drag of small arms projectiles, they roll out their radar unit. Rounds are fired and tracked by radar for very long distances, and if the radar is calibrated properly, trajectories can be recorded from which accurate and precise drag data can be obtained in very small increments, down to 1 foot if desired. ***The main problem with this approach is cost and access.*** Uncle Sam won't roll out the radar for just anybody, even if you do have the cash. You really have to know someone and be in the right place at the right time if you want to get radar data for small arms sporting bullets. Another problem with radar data is overkill. I've seen the raw data from these tests, and it's excessive. It takes a lot of time and expertise to make use of the results for just one shot, and frankly, all that detail isn't necessary. For small arms bullets that aren't guided or propelled, there's no need to have data for every foot of the trajectory. If you're just trying to measure BC, having data every 100 yards is plenty. The more important thing is the accuracy and precision of the data. Lapua has recently published some Doppler radar data for some of their bullets. Later in this Chapter I'll compare my drag measurements with the Doppler radar measured drag of some Lapua bullets.

The method I use to measure BC is based on measuring the muzzle velocity and *time of flight* to a known range. A detailed description of my process is presented in a later section. Before we get to that, I'll present a final test case that illustrates the advantages of referencing BC's to the G7 standard.

The Phoenix Test

In December of 2009, a test was conducted at the 1000 yard Ben Avery range in Phoenix, AZ. The purpose of the test was to measure BC's of some .30 caliber and 6.5mm bullets used in modern long range competition. The interesting thing about this test is that the BC's were measured in two independent ways, simultaneously.

A chronograph was placed at the muzzle, along with a microphone which started a *time of flight* timer. At 1000 yards, another timer was placed which provided the *stop* signal for the time of flight measurement. From this data, a BC was derived based on the muzzle velocity and time of flight.

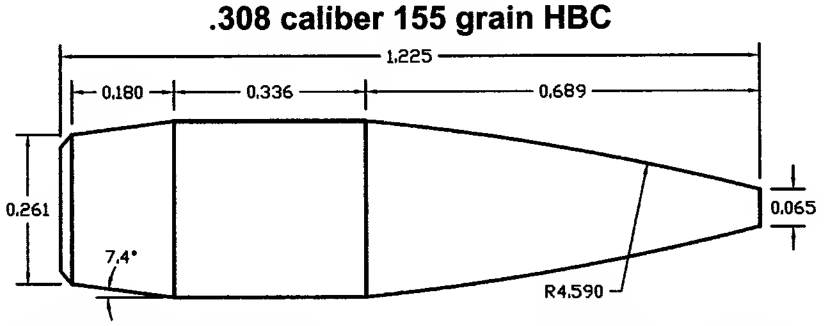
Also at 1000 yards, a special chronograph was placed to measure the remaining velocity. This special chronograph belongs to Middleton Tompkins who assisted in the test along with Michelle Gallagher and Eric Stecker of Berger Bullets. The special thing about Middleton's chronograph is that it doesn't use optical skyscreens. Instead, it uses large panels constructed of foam board covered with aluminum foil. As the bullet passes thru the special boards, it provides the timing signals to an Oehler chronograph. The panels of the chronograph are roughly 4' square, and specially constructed to measure remaining velocity at long range. So a second BC was derived for each bullet based on its initial and remaining velocity.

There are some insightful things to be learned from the results of this test.

Figure 2.10. Setting up Mid Tompkins Chronograph at 1000 yards

I'll use the Australian made .30 caliber 155 grain HBC bullet for a case study because of its remarkable resemblance to the G7 standard projectile (Figure 2.11).

Ballistic Coefficients were derived for this bullet from both the time of flight, and remaining velocity measurements. The raw data was used to derive BC's in reference to both the G1 and G7 standard projectiles. ***You'll notice that the G7 referenced BC is essentially the same for this bullet from both the time of flight and the remaining velocity calculations.*** However, the G1 referenced BC is quite different for the two measurement methods.



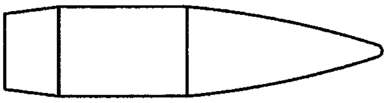
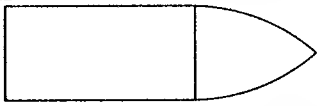
<table>
<tr><th colspan="2">G7 Standard Projectile</th><th colspan="2">G1 Standard Projectile</th></tr>
<tr><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>G7 BC from TOF</td><td>0.236</td><td>G1 BC from TOF</td><td>0.468</td></tr>
<tr><td>G7 BC from Velocity</td><td>0.235</td><td>G1 BC from Velocity</td><td>0.455</td></tr>
</table>

Figure 2.11 BC measurements are less prone to error when a more representative standard is used in testing.

You can conclude from the data presented in Figure 2.11 that if you reference the proper standard projectile when measuring the BC of a bullet, the results don't depend on *what* you measure (TOF or remaining velocity). However if you use a poorly matched standard, the measured BC *does* depend on what method you use to measure.

Putting this error into practical terms, imagine if you wanted to calculate a trajectory with the BC's that you measured directly from testing. If you're referencing the G1 standard projectile, you will measure a BC of either .468 or .455 (a difference of 2.4%) depending on what method you used to measure (TOF or velocity). So if you calculated a trajectory to 1000 yards for this projectile at 3000 fps muzzle velocity in standard conditions, you would calculate the drop to be either 311.7", or 318.9", a difference of 7.2" of predicted drop.

However, if you referenced the BC to the proper standard (G7 in this case) you will measure a BC of either .236 or .235 (a difference of only 0.4%) depending on the method used to measure it. (note that a difference this small could easily stem from experimental error). Now if you calculated a trajectory to 1000 yards for this projectile using the G7 BC under the same conditions, you will calculate the drop to be either 311.0" or 312.1", a difference of 1.1" of predicted drop.

The Phoenix test provided a unique opportunity to learn about measuring BC's and the effects of referencing to various standards. Here are some other interesting facts that were learned/confirmed in the Phoenix test:

- A G1 BC derived from TOF will result in a more accurate trajectory prediction than a G1 BC derived from velocity. Consider the example presented above. The G1 BC of .468 that was derived from TOF resulted in a predicted drop of 311.7". This compares well to the G7 predictions of 311.0" and 312.1". The G1 BC derived from velocity predicted a drop of 318.9" which is the outlier. It should be no surprise that drop is better predicted from a TOF derived BC. After all, drop results from gravity acting to *accelerate* the bullet down according to *how long* (time of flight) the bullet is exposed to gravity.
- The projectiles that are shaped *less like the G7 standard* had G7 BC's that were proportionally different depending on how they were measured. In other words, the G7 standard isn't a *perfect* match for *all* bullets, and the farther the bullet shape gets away from the G7 projectile, the more its TOF and velocity derived BC's will depart. However, for all the bullets tested, the G7 BC's had less variation than the G1 BC's. Specifically, the average error between TOF and velocity derived data was 0.9% for the G7 referenced BC's, and 2.8% for the G1 referenced BC's.

It should be noted that if you're intent of measuring BC is to establish a relative comparison of bullet performance, then it doesn't matter if the measurements are accurate as an absolute magnitude. In other words, if you just want to know how the BC's compare, then the velocity derived results are perfectly valid no matter which reference standard is used. It's only when you want to use the BC to predict truly accurate trajectory metrics (drop, remaining velocity, etc.) that you need a properly referenced BC.

In this next section, I'll explain the equipment, procedures, results, and uncertainties involved in the BC measurement technique that I've developed. This is the method used to produce all of the data in *Ballistic Performance of Rifle Bullets*.

Description of My Process for Measuring BC's

The basic idea of my test procedure is to measure the bullet's muzzle velocity and time of flight at several (3 to 5) points as it flies down range. Then a special ballistics program is used to find out what drag would result in the observed times of flight, given the measured muzzle velocity and atmospheric conditions.

Acoustic sensors and wireless transmitters are used to detect the *crack* of the bullet's supersonic passage, so this testing method only works on the portion of the bullets trajectory that's supersonic.

The main advantage of acoustic sensors over optic sensors is range. Optic sensors only work over short distances, and need a suitable background (diffuser) to work properly. This again presents the shooter with the challenge of shooting thru a small window. Acoustic sensors, by contrast, can detect the loud supersonic crack of the bullet from tens of feet away. This makes them a much more practical sensor for detecting the passage of bullets at long range.

The sensors are placed in 200yard intervals. The distance from the bullet's flight path to the sensors must be known with reasonable accuracy so the time lag of the sound traveling from the bullet to the microphone can be accounted for.

The raw test data is a sound file for each shot that shows spikes in 200yard increments for the bullet's flight from muzzle to target. The times associated with the spikes are entered into a custom ballistics program designed to test a range of drag values until the predicted times of flight match the measured times for each interval. ***The benefit of using multiple times of flight is that it allows you to determine the unique shape of the drag curve for each bullet as it flies downrange.*** This isn't possible if you only measure the bullet's total time of flight at one range. When you know the drag of the bullet at all velocities, you can determine which of the standard drag functions (G1, G7, etc.) is the best match for the particular bullet, and how much the BC varies with velocity.

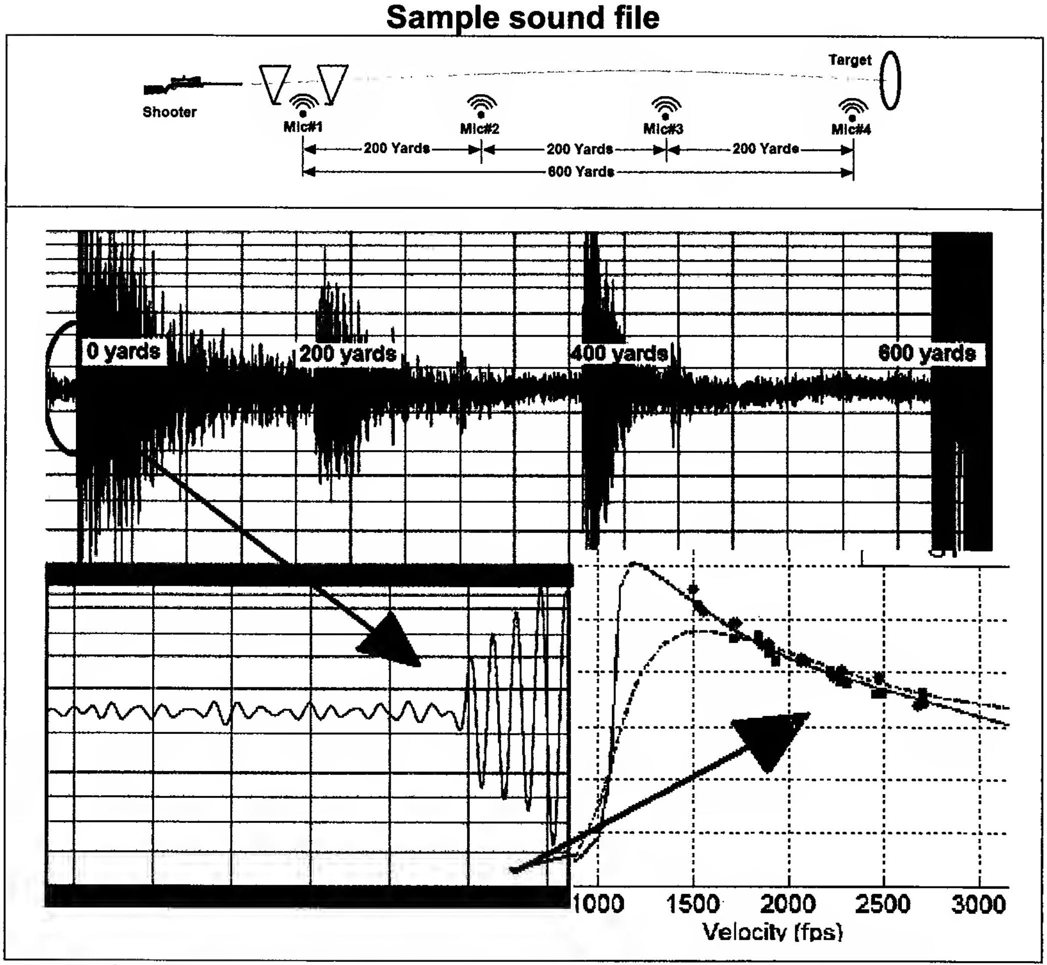


Figure 2.12. In this example audio file, the spikes indicate when the bullet passed by each of the 4 acoustic sensors. By zooming in on the spikes using audio processing software, the time of flight can be resolved with great precision.

Fundamental Sources of Measurement Uncertainty

My standard is to measure BC within +/- 1% error or less. In order to do that, all of the measurement errors involved in the process have to be kept to an absolute minimum. Each of the following categories of measurement uncertainty (error) affects the measurement of drag and ballistic coefficient and will be addressed separately:

1. Muzzle velocity
2. Distance from chronograph to microphones
3. Time of flight to microphones
4. Air Density

Muzzle Velocity Uncertainty

Measuring the muzzle velocity of bullets is something that most serious shooters are familiar with. It is equally well known that not all chronographs are created equal. In the early stages of my testing, I used an Oehler Model 35 chronograph with 8 foot screen spacing to measure muzzle velocity. Longer screen spacing is favored because it usually provides better accuracy. For example, if there is 1/8" error in screen spacing for screens that are 2 feet apart, the measured velocity will be off by about 15.6 fps for a bullet traveling at 3000 fps. However, that same 1/8" error in screen spacing only results in 3.9 fps error for screens that are 8 feet apart.

Currently, the Applied Ballistics Laboratory employs an Oehler chronograph with sensors set on a 12-foot spacing. This unit is set up indoors with artificial lighting. This set up is very reliable, and is used for all BC testing done at the Applied Ballistics Lab. When serious work is done outside the lab, chronographs are used which have verified accuracy compared to this 12 foot set-up.

Modern Advancements in Long Range Shooting – Vol 1 contains a thorough analysis of various chronographs and compares their accuracy and precision capabilities. To summarize the high points, most all chronographs are able to measure precisely, meaning that they will likely give you good Standard Deviations (SD's) for you muzzle velocity. However, if you want an accurate *average* muzzle velocity, then the units with longer screen spacing are better. As a rule of thumb, if a chronograph has greater than a 2-foot screen spacing, then it's likely to get within +/- 10 fps of the true average MV. Screen spacings shorter than 2-foot are likely to have more error.

Range Uncertainty

The range at which the acoustic sensors are placed downrange must be known with a high degree of accuracy. My acoustic sensors are capable of 0.0005 second (1/2 millisecond) resolution. While traveling at 2600 fps, a bullet will cover 1.3 ft in that amount of time. Therefore, in order to take full advantage of the acoustic sensors at all bullet speeds, range must be known to within +/- 1.3 feet. In order to achieve this level of accuracy in range measurement, two tools are used. The first tool is a 300' tape measure that is wound out in successive lengths to mark distance. Then range is re-checked with a *Nikon Monarch Gold Laser 1200 long-range* laser range finder. Both methods of measurement are used except where terrain prevents the proper use of the tape measure, in which case the laser is used by itself as the only range measuring unit.

The accuracy of the laser rangefinder is stated as +/- 0.5 yards (1.5 feet). The accuracy of the tape measure is somewhat better than that, but kind of depends on how carefully it's used. It would take about +/- 4 feet of range uncertainty at 600 yards to cause +/- 1% error in measured BC. With the tools and practices that I use to measure range, I'm confident that I'm measuring range to within half that error (+/- 2 feet at 600 yards). Therefore, range measurement uncertainty is within the acceptable error budget.

Bullet Time of Flight Uncertainty

The bullet time of flight that's used to calculate BC is determined from the recorded audio files, and can be identified with limited resolution. With the acoustic hardware and software I'm using, I can determine the passage of the bullet by the sensors to within +/- 0.5 ms (+/-0.0005 seconds) error. Even with a short 200 yard interval, this uncertainty in time results in less than +/- 1% error in measured BC. Therefore, error in the time of flight measurement is within acceptable error margins.

Uncertainty of Air Density

The value of the measured BC is directly proportional to the air density, so it's very important to measure the atmospheric properties of the test site at various times during the day as testing is progressing and the air properties change. A Kestrel 4000 is used to monitor the air temperature, pressure, and humidity. Air density and speed of sound is calculated from these parameters. According to the stated accuracy of the Kestrel 4000 for temperature, pressure and humidity; air density and speed of sound can be calculate with less than +/- 1% uncertainty. Note: although the atmospheric conditions vary for each of my tests, the BC's published in *Ballistic Performance of Rifle Bullets* are all corrected to ICAO standard sea level conditions.

Summary of Uncertainty Analysis

The preceding uncertainty analysis was presented to illustrate the major sources of uncertainty that are present in this kind of BC test. The analysis was done as an exercise to show *approximately* how accurately each variable has to be measured. The real test of measurement precision comes when the test is performed multiple times. If the same bullet is measured in multiple tests, and the BC is measured to be the same within +/- 1% every time, then the desired precision has been achieved. ***This level of repeatability has been achieved many times with multiple bullets.*** In fact, every time I conduct a round of BC firing tests, several bullets are re-tested to compare with historical test data. This is one of the diagnostic measures in place to insure repeatability in the process. If there is ever more than +/- 1% error in a bullet's measured BC, I know there is a problem, and I don't proceed until the problem is identified and corrected.

The fact that the tests are repeatable is proof of their *precision*, but it doesn't guarantee anything about their *accuracy*. It's possible for a test to be repeatable, but be constantly inaccurate by the same amount for some unknown reason. There are several ways to verify the *accuracy* of the measurements. One way is to compare the measurements to other measurements of the same bullets that are known to be true. The best drag measurements possible are those made by Doppler radar testing. Lapua has published its Doppler radar test results for some of its bullets. The following

Figures present a comparison of my measured drag to the drag measured by the Doppler radar unit for some Lapua bullets.

As you can see in Figure 2.13, the measured data points that result from my acoustic testing lie (on average) directly on the drag curve measured by the Doppler radar results. Furthermore, the drag curve for this bullet was measured by the Doppler radar test for its entire range of velocity, and found to be a near identical match to the G7 standard drag curve above 1000 fps. Below 1000 fps you can see the drag diverges dramatically from the G7 standard drag curve. I believe that's due to the bullet becoming unstable and tumbling during its flight, causing much elevated drag below transonic speed. The G7 drag curve shown in Figure 2.13 has been scaled by a form factor of 1.164 in order to match the measured drag of this bullet.

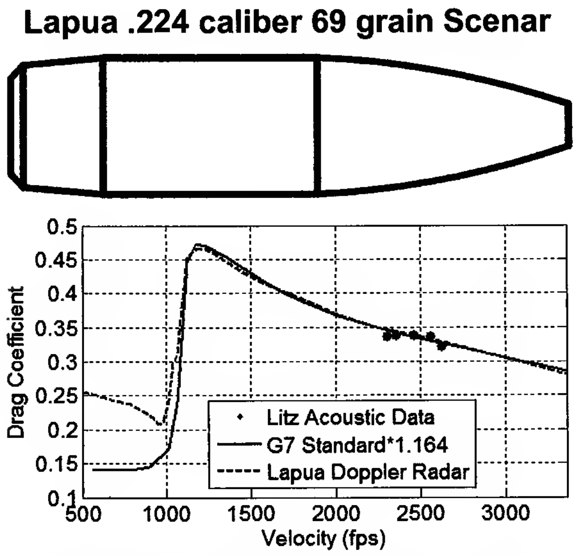


Figure 2.13. My acoustic drag measurements compared to Lapua's Doppler Radar drag measurements.

To clarify the nature of the experimental data points, they always have some amount of scatter. For this particular bullet, the (Litz measured) drag data does not span a wide range of velocity. However, by matching up the G7 drag curve to the measured data points (with the form factor of 1.164), the drag is accurately predicted at higher and lower velocities as indicated by the Doppler Radar measurements. If my measured drag points were used to scale the G1 curve instead of the G7 curve, the extrapolated drag would be way off for higher and lower velocities.

The next bullet has already been the subject of some analysis earlier in this chapter. Figure 2.14 shows how my acoustic measurements of supersonic drag compare to the Lapua Radar data. Also, as in the case with the .224 caliber 69 grain Scenar, this bullet exhibits a near identical match to the G7 drag curve at supersonic speed.

Lapua 6mm 90 grain Scenar

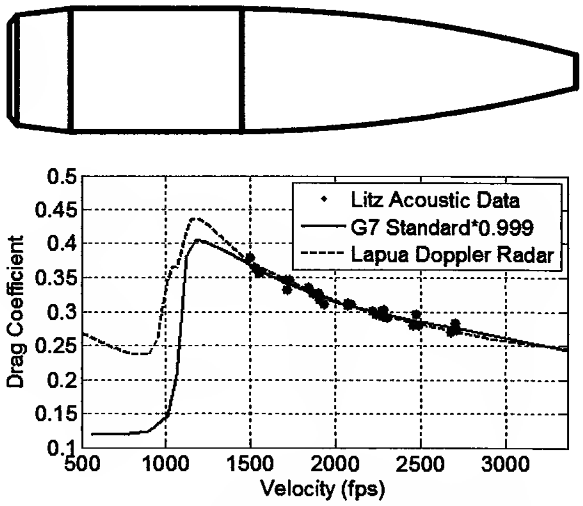


Figure 2.14. My acoustic drag measurements compared to Lapua's Doppler Radar drag measurements.

You can see that below 1500 fps the Doppler measured drag begins to rise above the G7 standard drag curve. This happens either because it's the true drag of the bullet as it flies perfectly nose forward *or* the elevated drag is due to the bullet beginning to fly with some amount of *coning motion,* possibly due to the onset of a dynamic instability that's brought on as the bullet approaches transonic speed. At a speed of about 1100 fps (very near the speed of sound), the Doppler measured drag rises sharply, indicating catastrophic tumbling. The behavior of the bullet below supersonic speed is interesting, but rarely of consequence since we try to keep our bullets supersonic for their entire flight. There will be more discussion on the nature of dynamic stability at transonic flight speeds in Chapter 10 on stability.

Lapua .30 caliber155 grain Scenar

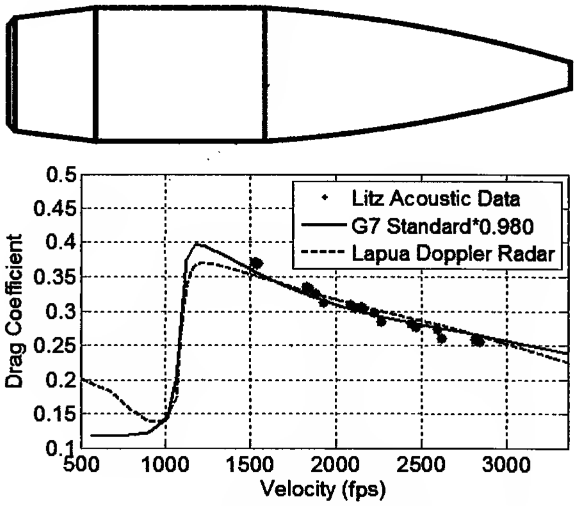


Figure 2.15. My acoustic drag measurements compared to Lapua's Doppler Radar drag measurements.

The next bullet that's compared is the .308 caliber 155 grain Lapua Scenar. The *Litz* acoustic test data points are the combination of two separate tests done for this bullet. The data points matched so well between the two tests, they're indistinguishable.

The final bullet that I'll present comparison data for is the Lapua .308 caliber 185 grain Full Metal Jacket Boat Tail (FMJBT), designated D46 by Lapua. This bullet has a unique feature; a rebated boat tail. The details of rebated boat tails are presented in Chapter 16. For now, simply note that the presence of the rebated boat tail does nothing to compromise the match of this bullets drag curve to the G7 standard. The match is nearly identical.

Lapua .30 caliber185 grain FMJBT (D46)

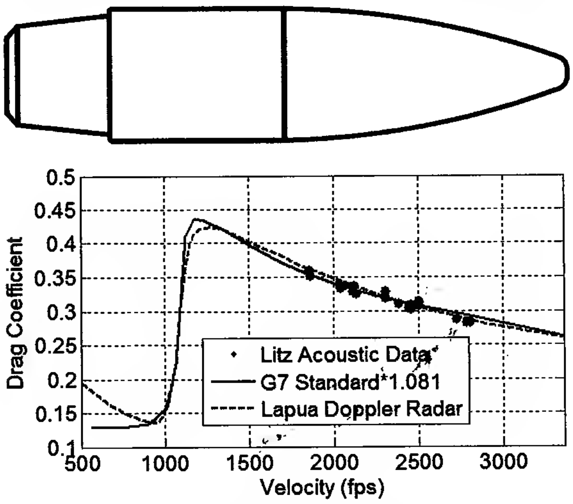


Figure 2.16. My acoustic drag measurements compared to Lapua's Doppler Radar drag measurements.

Conclusion

This is one of the most important chapters in the book because the issues surrounding ballistic coefficient and the benefits of referencing it to the G7 standard projectile are poorly understood within in the long range shooting community. *It is my sincere hope that this book will begin a genuine paradigm shift for the small arms industry in which G7 BCs are adopted by bullet makers and shooters as the standard for long range bullets*[2]. There are too many good things about this change to doubt that it's inevitable. It's just a matter of time until the collective masses recognize the handicapping effects of using BCs referenced to the old G1 standard. Before today's terrific, high quality shooting components (laser rangefinders, precise scopes, custom barrels, premium bullets, etc.) became available; errors incurred by the use of an incorrect drag standard were overshadowed by other, greater errors. We've reached the point where hits on small targets at long range are possible with available components, but are being limited by our ability to calculate accurate trajectories.

The explanation of my experimental procedure for measuring BCs was presented with an accompanying uncertainty analysis. Using this method, BC measurements have proven repeatable within +/- 1%. The experimentally obtained bullet data published in *Ballistic Performance of Rifle Bullets* is the most extensive and accurate collection of measured BCs ever compiled for modern long range bullets. Analysis based on this data will provide an unprecedented degree of accuracy and relevance to long range shooters' needs.

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[2] Note for the third edition: As of 2015, several major bullet brands including Berger, Lapua, Cutting Edge and Nosler are now providing G7 BC's for their bullets. This represents a great step forward for the industry. Hopefully one day the G1 standard will be dropped all together.

Chapter 3: Gravity Drop

Bullet drop is the most fundamental issue in external ballistics. If a rifleman is to have any chance of connecting with distant targets, he must completely understand the mechanism of bullet drop due to gravity. In keeping with the spirit of this book, I'll avoid the lengthy equations and stick to the relevant concepts that will help shooters hit targets at long range. It should be noted that this chapter is most relevant to hunters, or long range field shooting where the range to the target changes, or is uncertain. The effects of bullet drop are of little concern to conventional target shooters, be it Benchrest, F-class or high power.

The reason why target shooters don't care about bullet drop is because the range to the target is usually known. Once the sight setting is established for a particular yard line, it's always nearly the same. Target shooters only need a ball park estimate of drop in order to hit paper the first shot. After that, the sighter shots are used to center the group, and then the *record string* is fired. What I'm saying is, studying the subtleties of bullet drop is not necessary for successful KD (known distance) target shooting. On the other hand, long range hunting, or any other kind of shooting that's done at non-fixed ranges is different. With this kind of shooting, there are no sighter shots. The first shot has to be accurate. This puts an incredibly high demand on the shooter to understand the trajectory of his bullet so he can place that first round where it needs to go.

In this chapter, I'll explain some fundamental concepts related to the ballistic trajectory that will enable shooters to judge the merit of a particular round for a given application. This is not the chapter that explains how to calculate a trajectory. Chapter 8 contains the instructions for running the included ballistics software. For now, we're just talking about general concepts that apply to any trajectory.

Point Blank Range

The best way to describe point blank range (PBR) is with an illustration. Figure 3.1 shows a point blank range trajectory for a 5" target, which is typical of a varmint size target. In words, PBR is defined as ***the range at which the trajectory remains within a given target area.***

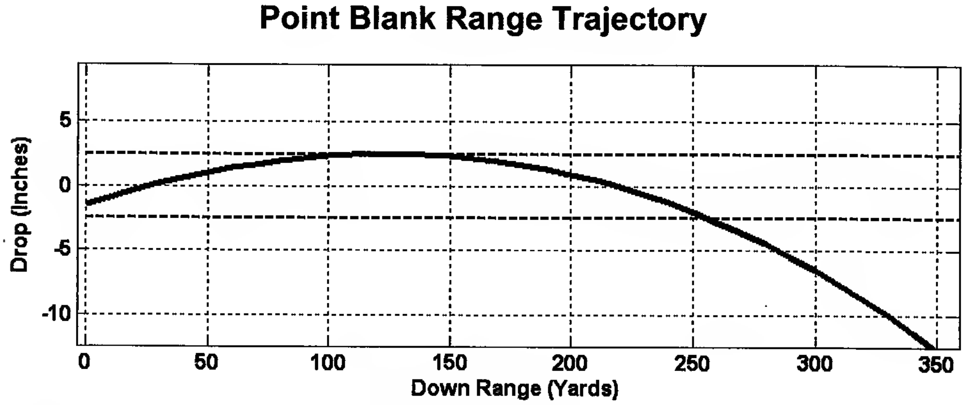


Figure 3.1. Point Blank Range for a 5" target.

You can see in Figure 3.1 that the trajectory remains within +/- 2.5" of the line of sight until just past 250 yards. Point blank range is affected by the height of the scope above the barrel. Having a taller scope mount will extend the point blank range because the bullet starts out farther below the line of sight, and is launched at a greater upward angle as a result. Let's step thru the important parts of the trajectory in Figure 3.1 from left to right.

1. First, you can see the trajectory starts out 1.5" below the line of sight. That's because the muzzle is underneath the scope.
2. At 27 yards, the bullet climbs thru the line of sight. This is the first of two *zero points* on the trajectory.
3. Next, the apex (highest point) of the trajectory occurs at 125 yards.
4. At 219 yards, the trajectory crosses back thru the line of sight for the second time.
5. Finally, at 257 yards, the trajectory falls 2.5" below the line of sight.

In other words, ***with a 1.5" sight height, you have to zero at 27 yards or 219 yards to achieve the point blank range of 257 yards for a 5" target.*** Of course, these numbers apply only for this specific combination of bullet, velocity, sight height and target size.

Most of the time, you're limited as to the distances that you can place targets for zeroing. For example, public shooting ranges have impact berms at fixed intervals (100, 200, 300 yards, etc.). This makes it difficult to zero the sights at some random range like 219 yards. To get around this, you simply determine where the trajectory is at the range you *can* shoot, and adjust the sights to hit the desired point at that range. For example, the point blank range trajectory in Figure 3.1 is 2.35" above the line of sight at 100 yards. Given a 100 yard range, you can adjust the sights so that the bullets impact 2.35" above the aim point and the sights will be properly set for the 257 yard point blank range for a 5" target with this particular trajectory. In another example, let's say you have only a very short range to work with. You can place a target anywhere up to 30 yards. In this case, I would place the target at 27 yards and adjust the sights to hit dead on. This is the same sight setting as a 219 yard zero, and results in the same 257 yard point blank range. A word of caution when setting sights based on short range firing: ***errors in short range zeroes are magnified at long range.*** For example, if your zero is ¼" off at 100 yards, that's equal to only 2.5" of error at 1000 yards. However, if you have the same ¼" error in a 25 yard zero, it results in 10" of error at 1000 yards. Parallax is an optics problem that can cause problems at long range for short range zeroes as well.

The concept of PBR can be useful to hunters. By using the vital area of the game as the target size, point blank range is the range at which the animal can be killed without any adjustment to the sights, so the theory goes. Personally, I think that using point blank range in such a way is a sloppy way of doing things. Not making sight adjustments for a target that's within PBR means possibly accepting shots at the extreme top or bottom of the vital zone. Let's just say you shoot at a target that's roughly half way to point blank range where the bullet is near its apex, and is expected to hit near the top of the vital zone. Now let's say that particular round was a little fast, and the first shot goes a little high due to the cold barrel. Furthermore, under field conditions, your hold may be less than perfect and maybe the shot breaks a touch high. It doesn't take much before the errors combine and result in a miss, high in this example. It would be much better to adjust the sights for an impact in the center of the vital area, even if the target is within PBR. This way small errors are less likely to cause a miss. Having said that, point blank range is still a useful concept to consider in some situations. For example, when fast shots must be taken and deliberate sight adjustments are not possible.

Advantage of a flat trajectory

When someone says a rifle shoots *flat*, it means the trajectory doesn't have much arc, and remains close to the line of sight for a greater distance. A flat trajectory has the effect of extending the point blank range. ***Fundamentally, a flat trajectory is desirable because it's more forgiving when the range to the target is uncertain.*** For example, if you judge a target to be 250 yards away and adjust the sights accordingly, and target is actually 300 yards away, the bullet will strike lower than you intended, possibly causing a miss. If the rifle shoots *flat* enough, then the bullet may remain close enough to the line of sight to result in a low hit instead of a miss.

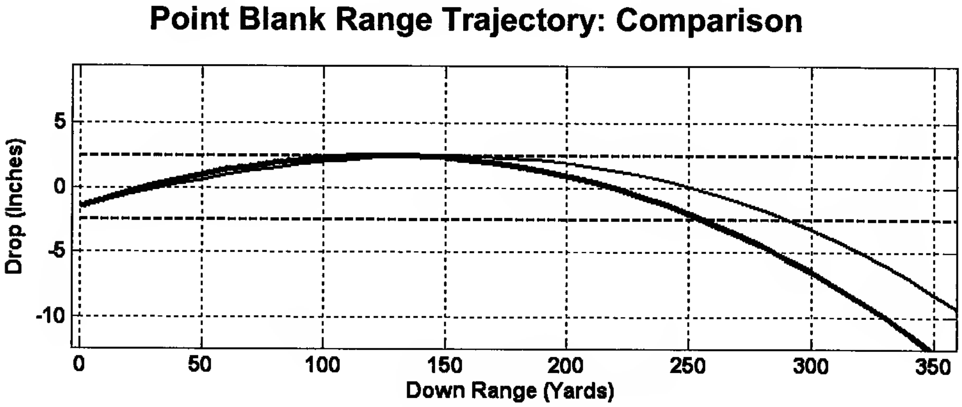


Figure 3.2. The point blank range is greater for the flatter trajectory.

Figure 3.2 compares two point blank range trajectories. The heavy line is the same trajectory we studied in the previous section. This heavy line represents a larger caliber bullet with a higher BC, fired at a lower muzzle velocity. The thin line represents a smaller caliber, lower BC bullet, fired at a higher muzzle velocity. *Over short range*, the smaller faster bullet results in a flatter trajectory, and a greater point blank range. Again, the benefit of the flat trajectory is that it makes precise range determination less critical.

Side effect of a flat trajectory

Consider the success of rounds like the .220 swift and the .22-250 for varmint hunting. These cartridges fire light bullets at extremely high velocity. High velocity is key to a flat trajectory, however there is a downside to achieving a flat trajectory: excessive wind drift. Chasing high velocity in an effort to flatten the trajectory means using bullets that are light for the caliber. Such light bullets have lower BCs, and therefore (usually) have more wind drift. This is a big problem because next to drop, wind drift is the next most common cause of missing targets (sometimes it's more dominant than drop). So the basic compromise when choosing a round for hunting in field conditions is between a flat shooting round and a high BC. At one end of the spectrum you have the .220 Swift, which is extremely flat, but not very good at resisting wind deflection. At the other end of the spectrum is something like the .308 Winchester, loaded with heavy bullets. This round will not shoot flat, but will drift far less in the wind compared to the .220 Swift. Many hunters find a compromise somewhere between these two extremes. The .243 Winchester is a good balance between a flat shooting round with some ability to resist wind deflection. You can choose bullets for a particular rifle that will make it more or less flat, and more or less wind sensitive. In the case of the .243, you have bullets from 58 grains up to 115 grains to choose from.

Range Finders

Most of the previous discussion about flat trajectories is well understood by serious hunters, especially varmint hunters. What I'd like to discuss now is the paradigm shift that was caused by the advent of affordable laser range finders. ***Laser range finders effectively erase the merit of a flat shooting round.*** Think about it, if you can use a laser range finder to accurately measure the range to the target, then what's the benefit of a flat trajectory? By erasing range uncertainty from the equation, you no longer have to compromise between a flat shooting round and one that's good in the wind. You can simply choose the round that's best in the wind! A shooter who fully understands this paradigm shift can take full advantage of the laser range finder by choosing a heavier round that's better in the wind. In a round-about way, the range finder can be effectively responsible for reducing wind deflection!

As long as the range to the target can be accurately measured with the rangefinder, the excessive drop of the slower, heavier round can be effectively accounted for. Of course, you need some basic information about your rifle/ammo in order to predict and correct for the excessive drop of the heavier round. One thing you need to know is the ballistic coefficient of the bullets you're shooting so you can enter it into a ballistics program and calculate the drop. Other pieces of information you need are: muzzle velocity, sight height, angle of inclination to the target and atmospheric conditions. There are more thorough instructions of how to use the included ballistics software in Chapter 8.

Despite all the wonderful things that range finders do for the long range rifleman, they are certainly not a cure-all in every situation. Not everyone can afford one, and they don't always work reliably in all terrain, on all targets, or in some light conditions. For situations when range finders cannot be used effectively, a flat trajectory remains a valuable measure of merit.

Trajectory Comparisons

I would now like to discuss another measure of merit related to bullet drop that's not new to the field of exterior ballistics, but is seldom discussed. It's called *danger space.* Danger space is related to point blank range, but it's different, and will be described below.

In the classic trajectory comparison between two rounds, a ballistics program is run with nominal conditions, usually standard sea level atmosphere, 1.5 inch scope height and a 100 yard zero. The trajectory is predicted beyond the zero point, and you can see how the total drop compares beyond that point. Naturally, the round with the least amount of total drop is said to have a "superior" trajectory.

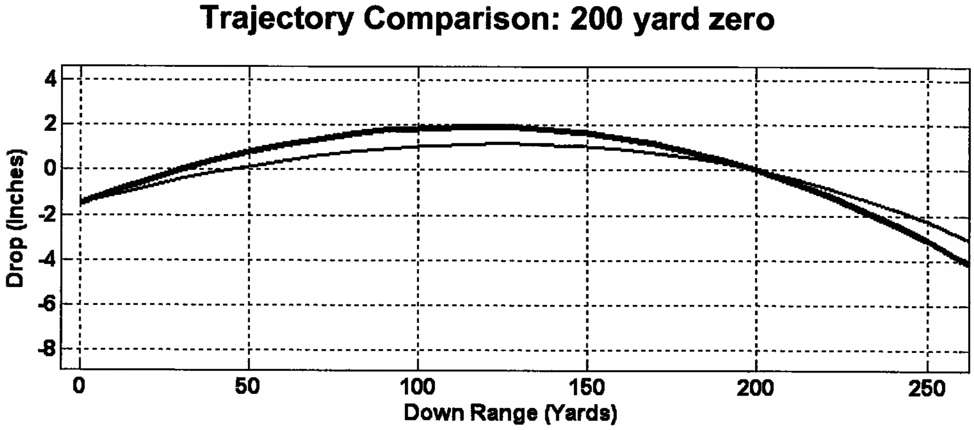


Figure 3.3. Illustrating the *flatness* of a lighter faster round at close range.

In the previous discussion about flat trajectories, I stated that cartridges like the .220 Swift, and the .22-250 produce flatter trajectories than something like the .308 Winchester.

This is true *over short distances*, but if you consider the trajectory at long range, you can see that the .308 Winchester *catches up* to the smaller round. It's kind of like the tortoise and the hare. In a short race, the hare wins. If the race is long enough, the tortoise, slow and sure, can outlast the hare. Consider the trajectories in Figure 3.3. Again, the thick line represents a bigger, slower bullet with a higher BC (like a .308 Winchester), and the thin line represents a small, high velocity bullet with a lower BC (like a .22-250 or .220 Swift). Notice that the smaller faster round has a flatter trajectory. Even beyond the 200 yard zero point, the trajectory remains closer to the line of sight than the trajectory of the slower, heavier bullet.

You can see that the lighter faster round rises just over 1" above the line of sight on its way to the 200 yard zero, while the bigger, slower round rises nearly 2" to arrive at the same zero point. By 250 yards, the flatter trajectory of the light, fast round is only 2" below the line of sight, while the heavier, slower round is 3" low. Clearly, at short range, the smaller, lighter round with the lower BC and higher muzzle velocity has a flatter trajectory. How do these two rounds compare at greater ranges? Figure 3.4 shows how these trajectories compare beyond 250 yards.

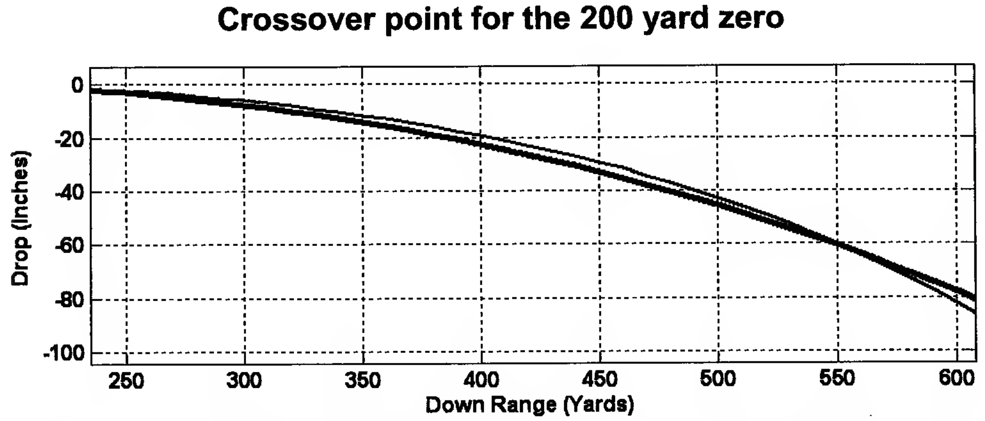


Figure 3.4. The geometric crossover point is at 550 yards for these two trajectories that are both zeroed at 200 yards.

You can see that up until about 550 yards, the lighter faster round has less total drop than the slow heavy round, after which point, the trajectories cross, and the heavy round has less drop. Somewhere around 450 yards marks the range at which the trajectory advantage is greatest for the light, fast round. At 450 yards, the drop of the light fast round is 29", while the slow heavy round is 33", a difference of 4". After the trajectories cross at 550 yards, it only takes the heavy round 50 yards to be 4" ahead of the light round (78" vs 82" of drop). The advantage quickly grows in favor of the heavy round.

What allows the big heavy round to *catch up* to the lighter round like it does? The answer is ***velocity retention***. The light round may start out at a blistering 3600 fps, and the heavy round a sluggish 2750 fps, but ***since the heavy bullet has a higher BC, it retains its velocity better than the lower BC bullet.*** This results from the basic definition of ballistic coefficient; a relative measure of how well a bullet *penetrates the air,* and retains velocity.

The trajectory represented by the thick line represents a .308 175 grain bullet at 2750 fps. The trajectory represented by the thin line is a .224 caliber 40 grain bullet at 3600 fps. Here are some interesting comparisons between the two trajectories:

1. Even though the lighter bullet started out 850 fps faster at the muzzle, both bullets have slowed to the same speed (2250 fps) by 290 yards. Beyond that, the larger bullet is actually faster than the smaller bullet.
2. At 290 yards, the light bullet has lost 38% of its original velocity, and the heavy bullet has lost only 18%.
3. The time of flight for the light bullet is less at 290 yards because it had a higher initial and average velocity. It's not until 510 yards that the times of flight match at 0.6663 seconds.
4. At 510 yards when the time of flight is equal for both bullets, they have had the same average velocity to that point. It's near this point (510 yards) that the trajectories cross (550 yards).

So far this has been very mainstream stuff about trajectory comparisons. The conclusion that's typically drawn from the type of comparison made above is that the lighter, faster round is *superior* in trajectory up until about 550 yards. Beyond that, the heavier, higher BC bullet is better because it has less drop after 550 yards. Judgments about the relative merit of ballistic trajectories based on the geometric crossover points are very common, but are fundamentally flawed.

This basic drop comparison has been made countless times, printed on thousands of boxes of ammo, and almost everyone reaches the same wrong conclusion about the point at which one trajectory gains or loses the advantage. It's an easy mistake to make, because the trajectories literally *cross-over* on the plot. However, ***the point where the trajectories actually cross is not the point where one trajectory becomes superior to the other.***

There are several reasons why the geometric cross over point is insignificant. First of all, the geometric crossover point is not fixed; it depends on where the sights are zeroed. Look at Figure 3.5 and notice where the trajectory crossover point is when the two trajectories are zeroed for 100 yards instead of 200 yards.

The trajectory *crossover point* has moved from 550 yards to 600 yards when the zero range changed from 200 yards to 100 yards. If the zero range were 300 yards, the crossover point is at 490 yards. That's a difference of 110 yards in the crossover point just by changing the zero from 100 to 300 yards. Furthermore, the crossover points are also affected by sight height.

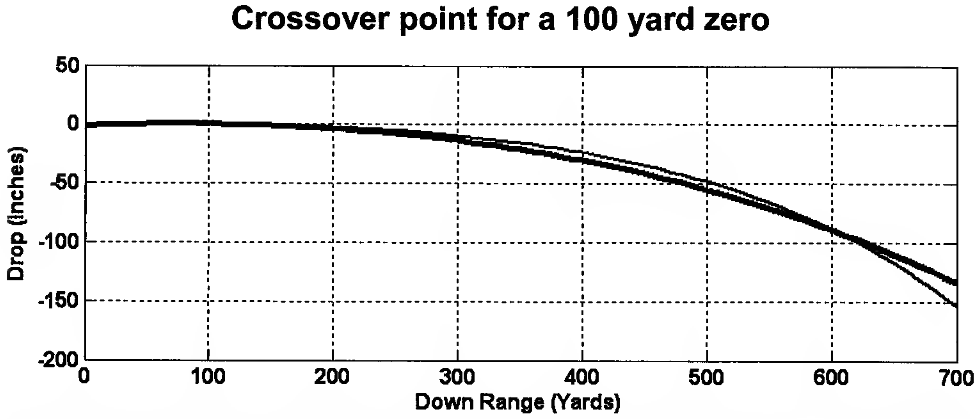


Figure 3.5. When zeroed for 100 yards, the trajectory crossover point is at 600 yards.

It is impossible to determine what range one trajectory becomes better than another using crossover points. Therefore, the geometric point at which the trajectories cross over should not be used to determine the relative merit of trajectories.

So what's the big deal? The point is; we need a way to determine the *genuine* merit of trajectories so we can determine which trajectory is ***better.***

Whatever method we choose, it had better be consistent, unlike the geometric crossover point illustrated above.

What does it really ***mean*** to say that one trajectory is *better* than another? What is the fundamental quality that we're trying to measure? I define a quality trajectory like this: ***A quality trajectory is one that makes it easier to hit a target!*** Who can disagree with that? After all, that's what this entire book is about; presenting information that can be used to more easily hit targets. There is a very fundamental and effective concept in external ballistics that can be used to determine the genuine quality of a trajectory. It's called the *danger space.* I didn't invent it, but I would like to reintroduce this very old and useful idea to shooters who can use it to make better-informed decisions that result in more holes in distant targets!

Danger Space

Danger space is the true measure of merit for a trajectory. Unlike the misleading and inaccurate geometric crossover point method that's been used to compare trajectories for generations, the danger space is a more consistent and true measure of quality for ballistic trajectories. Using danger space, one can determine the trajectory that's most likely to result in hitting a target at a given range.

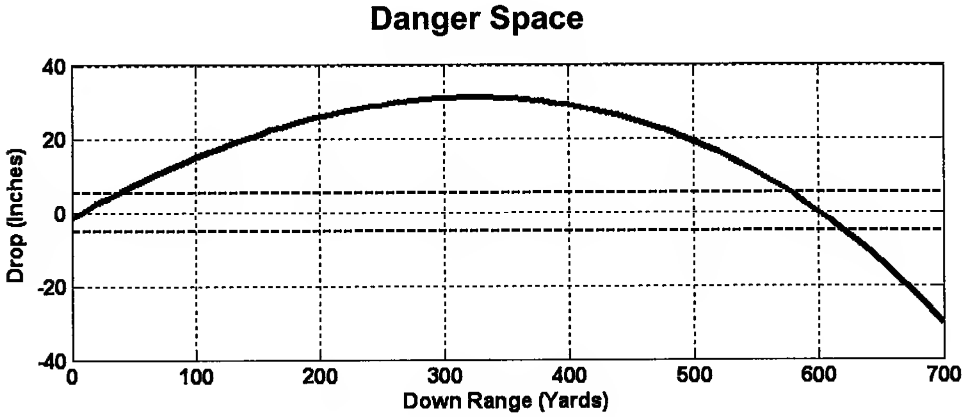


Figure 3.6. Danger space for a 10" target at 600 yards.

Danger space is a lot like point blank range. As such, it's best described with a picture. Figure 3.6 illustrates the danger space for the high BC .30 caliber bullet at moderate muzzle velocity and a 10" target at 600 yards. As you can see, the trajectory of the high BC bullet *occupies the height of the target* from 579 yards to 620 yards. This means that the 10" target is in the ***danger space*** of the trajectory for 41 yards (from 579 to 620 yards). Naturally, longer danger spaces increase the likelihood of a hit on the target. ***A long danger space is less sensitive to errors in range determination and muzzle velocity variation.*** Because of the preceding statement, we can use danger space as a genuine measure of quality for trajectories. A trajectory with a long danger space makes it easier to hit the target.

Figure 3.7 shows the low BC danger space compared to the high BC danger space for a 10" target at 600 yards.

The danger space of the low BC trajectory only extends from 585 to 613 yards, a distance of only 28 yards. Clearly, the high BC trajectory has a greater danger space, and is better at 600 yards. Specifically, the high BC trajectory has a danger space that's 14 yards longer, which is 50% more danger space than the low BC trajectory.

Let's see how the danger space compares at different ranges, and find out where the advantage really changes from the low BC to the high BC trajectories. You can find the true crossover point simply by running trajectories for various zero ranges until the danger spaces are equal.

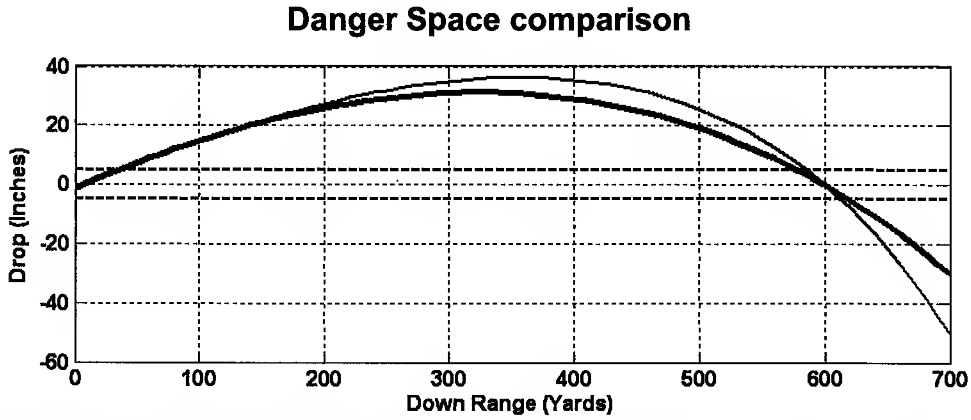


Figure 3.7. Danger space for a 10" target at 600 yards is longer for the slow and high BC round than the fast low BC.

Table 3.1 shows how the danger spaces compare for the two sample trajectories at various ranges. In this case, the real crossover point happens to be 405 yards. In other words, out to 405 yards, the low BC .224 caliber bullet produces the longer danger space, and the superior trajectory. Beyond 405 yards, the high BC .30 caliber bullet has a greater danger space, meaning it is more likely to result in hitting the target given the same set of range and muzzle velocity uncertainties.

It is possible to calculate danger space with traditional external ballistics software. There are a couple examples in the next section that illustrate how to calculate danger space with the included ballistics software.

	Danger Space	
Range	High BC Trajectory	Low BC Trajectory
400 yards	77.2 yards	77.7 yards
500 yards	55.1 yards	46.0 yards
600 yards	41.1 yards	27.6 yards

Table 3.1. Danger space comparison.

Another thing to point out about comparing trajectories using danger space is that target size doesn't have a very large effect on which trajectory is better. In other words, if the danger space analysis identifies a superior trajectory for a 10" target, that trajectory will also be superior for a 5" target, or a 15" target as well. ***Danger***

space is the absolute measure of merit that determines a superior trajectory. It just makes sense: if you want to increase the chances of hitting the target, choose the trajectory with the greatest *danger space*!

Some example calculations using danger space

Let's take a look at some trajectory comparisons and put the danger space concept to use. Consider the fast and flat varmint legend; the 220 Swift. Everyone knows about this rifle's legendary reputation with varmint hunters for its blistering high velocities and banjo string flat trajectories. How would the mighty 220 Swift compare to the relatively sluggish 243 Winchester at 700 yards?

The 220 swift is capable of 4000 fps with 52 grain bullets. The 243 can achieve about 2900 fps with 105 grain bullets. Over short ranges, there's no question that the 220 swift shoots flatter. Let's compare the danger space of these two trajectories at 700 yards to see which is better *way out there.*

A typical 52 grain .224 caliber bullet will have a G7 BC of about 0.112. The 105 grain 243 caliber bullet will have a G7 BC of about 0.272. We'll consider the danger space comparison for a target that's 10 inches high. Using the included ballistics software, we can compare the danger space of the two rounds at a particular distance by following these steps:

1. Input the variables associated with the first bullet (BC, velocity, etc.).
2. Set the zero range for whatever distance you're doing the danger space comparison for, in this case 700 yards.
3. Set the max range 100 yards past the zero range.
4. Set the range step size to 1 yard.
5. Click *calculate.*

The output of the ballistics program will be very long; 800 lines long in this case. Scroll down to the zero range and look for where the bullet came within ½ of the target size. In other words, our target size is 10 inches tall for this example and the trajectory is zeroed at 700 yards. At what distance does the trajectory come within 5 inches of the zero? Now do the same thing behind the zero range; find out how far beyond 700 yards the bullet goes before it drops 5 inches below center. Add the two distances together and that's the danger space.

Putting in all the variables for the 220 swift produces the a trajectory that's 5 inches above the 700 yard zero at 686 yards, and 5 inches below the zero at 713 yards for a total danger space of 27 yards. For the 243 Winchester with 105 grain bullets at 2900 fps, the bullet is within 5 inches of the 700 yard zero from 681 yards to 718 yards, a total of 37 yards. So in this example, the 243 with the slower heavier bullet has a greater danger space at 700 yards than the 220 Swift by 10 yards, which is 37% better. The advantage of the 243 will continue to grow as range increases.

The interested reader can repeat this process for closer ranges and determine at what range the 243 first achieves a *better* trajectory than the 220 Swift based on the danger space analysis.

Variation of Earth's Gravity

The standard gravitational acceleration of the earth at its surface is defined as 32.17 ft/s^2. Technically, this value varies slightly with altitude and with the local density of the materials at each point on the planet. Practically speaking, these small variations in the Earth's gravitational field are negligible for the purposes of computing ballistic trajectories for small arms.

Chapter 4: Uphill/Downhill Shooting

It's quite obvious that shooting uphill or downhill should affect the bullets trajectory, but it's not necessarily clear *why*. This is where a picture is worth 1000 words. Figure 4.1 shows how the components of gravity are related to the line of sight, and why the bullet has less *drop* when shooting uphill *or* downhill.

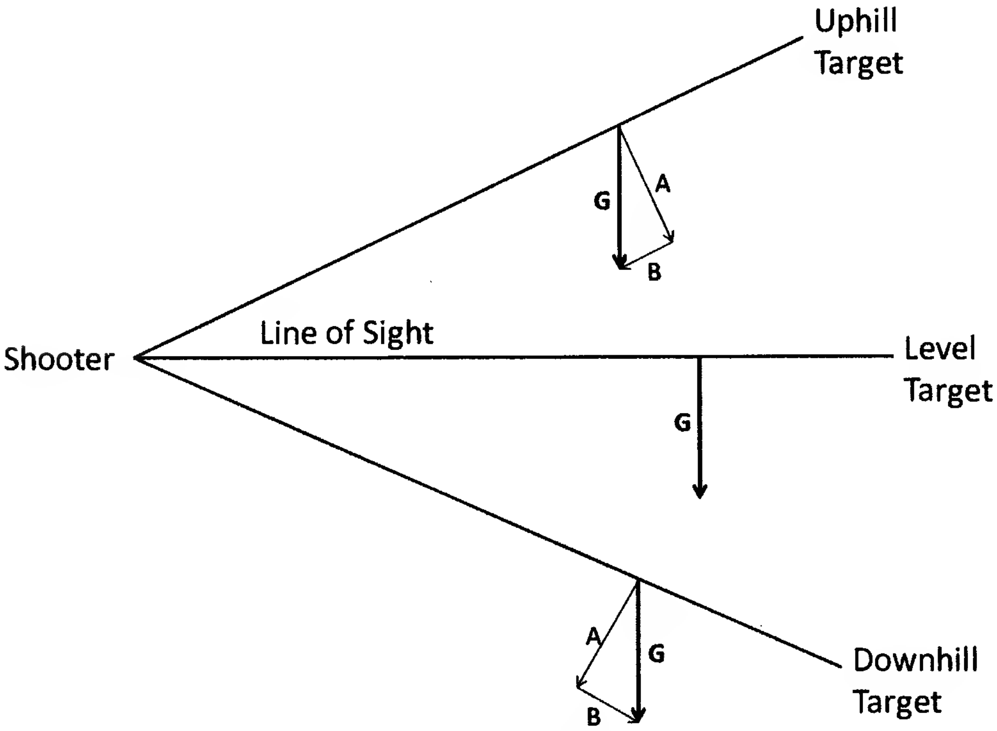


Figure 4.1. Effects of uphill and downhill shooting.

When shooting level, gravity pulls the bullet directly away from the line of sight. However, *when the line of sight is elevated either up or down, the* *pull of gravity is still straight down and no longer pulls the bullet directly away from the line of sight.* It's clear in Figure 4.1 that when shooting uphill, some of the effect of gravity is pulling the bullet away from the line of sight (A), and some of the effect of gravity is slowing the bullet down (B). When shooting downhill, some of the effect of gravity is pulling the bullet away from the line of sight (A), and some of the effect of gravity is helping the bullet maintain speed (B). *Since there is effectively less gravity pulling the bullet directly away from the line of sight, the bullet doesn't drop as far below the line of sight when shooting uphill or downhill.*

The net result is that shooting *uphill or downhill* will cause you to *hit high* if the effect of gravity is not properly accounted for. Most ballistics programs are able to account for the effect of uphill or downhill shooting angles on a trajectory. In general, small angles (less than 10 degrees) have a negligible effect. Larger angles, especially at long range, must be measured and accounted for.

The next two sections present a couple of quick and easy approximations that can be used to correct for angle shooting.

The *Riflemans Rule*

One way to approximate the effects of uphill and downhill shooting is to multiply the range-to-target by the cosine of the *look angle.*

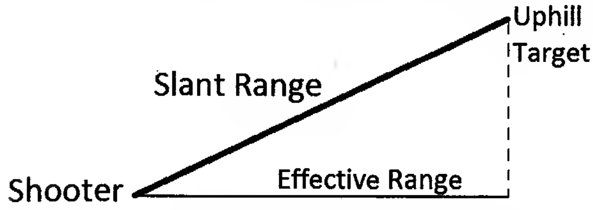


Figure 4.2. Effective range for Riflemans Rule.

This effectively gives you the horizontal range to the target. Look up the bullet drop for this reduced range, and that will be an approximation of the bullet drop for the inclined shot.

For level targets, the look angle is 0, so the range is multiplied by 1.0 and no correction is necessary. For a 10 degree *look angle,* the range would be multiplied by 0.985 (cosine 10° = 0.985) of the measured range, or slant range to the target. This is a convenient way to *approximate* the effects of uphill/downhill shooting, but it is not *exact.* There are two reasons why simple range scaling is not an exact calculation. First, the range scaling ignores the effect of the bullet slowing down as it travels thru all the air between the shooter and target. Second, range scaling ignores the component of gravity that's either acting to decrease or maintain the bullets speed. In addition, range scaling does not distinguish between uphill vs downhill shooting.

The *Improved Riflemans Rule*

A more accurate way of accounting for the effect of shooting on an incline is to use the slant range to the target, and scale the bullet drop for a level shot by the cosine of the look angle. For example, let's say you have a target at 600 yards, on a 20 degree look down angle. Your bullet drop for a

600 yard level shot is 72". Multiply 72" by the cosine of 20 degrees (0.94), and you get 72" times 0.94 = 68".

This is a much more accurate way to correct for look angles than the basic *Riflemans Rule.* However, there is an important catch that you have to remember when using the *Improved Riflemans Rule.* You must be working from a relatively short range zero like 100 yards. If your rifle is zeroed for 600 yards, the trajectory is 'zero' at 600. If you get an inclined shot at 600 yards, the *Improved Riflemans Rule* won't indicate any correction. Ideally this rule is best applied to the raw bullet drop from the muzzle, but the approximation is very good for a trajectory zeroed at 100 yards.

Fully correcting for the effects of look angles

There is a commercial device available from *Sniper Tools Design Co.* called an *Angle Cosine Indicator (ACI)* that's specifically designed to help shooters account for the effects of uphill and downhill shooting. The ACI is available in two versions. One version indicates the actual angle of the line of sight. This is useful for inputting directly into a ballistics program. The second option reads in *angle cosine* rather than degrees. The *angle cosine* is the number that you would multiply the range by to get the approximate scaled effect of uphill/downhill look angles when using the *Riflemans Rule,* or the *Improved Riflemans Rule.* The angle cosine is 1.0 for level fire, and decreases more with steeper angles.

Figure 4.3. Angle Cosine Indicator

Measuring and accounting for the effects of up/down hill look angles becomes more important for steeper angles. Not only is the magnitude of the effect greater, but the sensitivity is greater also.

Table 4.1 shows the effect of several look angles on the drop of a typical 155 grain .308 caliber bullet at 3000 fps muzzle velocity at a range of 1000 yards. The drop is referenced from a 100 yard zero. Notice that you can ignore an angle error of +/- 5 degrees from level and have less than 2" of error in drop at 1000 yards. However, if the line of sight is elevated by 45 degrees, a +/-5 degree error will result in about +/-20" of error.

Also note the difference between a 45 degree look up vs look down is -213.5" vs -205.2" (a difference of 8.3") which is the difference between gravity working *against* the trajectory vs gravity working *with* it.

Look angle	Drop
0 degrees	-309.9”
+5 degrees	-309.3”
-5 degrees	-307.9”
+40 degrees	-233.7”
-40 degrees	-225.5”
+45 degrees	-213.5”
-45 degrees	-205.2”

Table 4.1. Gravity effect of look angle on drop.

There is a secondary effect of shooting at inclination angles that is unrelated to gravity. When shooting at very steep angles over very long ranges, the effects of altitude on air density can become an issue. Consider a 1000 yard shot at a target that’s at a 45 degree look up angle. The bullet will climb over 2100 feet as it rises to the target. The air density at that altitude will be less dense than at the shooters altitude, which will affect the bullets flight. When shooting uphill, the bullet will be going thru thinner air as it climbs, where as a downhill shot will send the bullet thru ever thickening air. This effect is negligible for short and medium range shots at shallow elevation angles, but becomes increasingly important as the range and the inclination angles grow. As an example, consider the 45 degree *look up* shot from Table 4.1. The drop of -213.5” does not account for the effects of thinner air at higher altitudes. For that particular shot, the air density at the target (2121 feet above the shooter) will be only 94% of the air density at the shooter’s altitude. The *average* air density that the bullet flies thru is 97% of the value at the shooters altitude. I’m not aware of any ballistics programs that account for the effect of air density gradient on uphill/downhill shots. If you want to correct for the atmospheric effects of shooting at inclination angles, the best way is to apply a multiplier to the BC.

Remember that the relationship between BC and air density is 1:1, meaning that a given % change in air density has exactly the same effect as the same % change in BC. In order to account for the effect of air density gradient on an uphill/downhill trajectory prediction, a scale factor can be applied to the BC. The scale factor is based on the air density ratio between the shooter and target. The scale factor is:

$$f = 1 + 1.3X10^{-5} * h$$

Equation 4.1

Where:

f is the scale factor that multiplies BC
h is the difference in altitude between the shooter and target in feet. For targets above the shooter, h is positive. For targets below the shooter, h is negative.

As an example of how to apply equation 4.1, consider the 155 grain .308 bullet with a G7 BC of 0.233 fired at a muzzle velocity of 3000 fps at a target 1000 yards away at a 45 degree look up angle. Without making any correction to the BC, the drop below the line of sight for this shot is -219.3”. In order to calculate the effects of the air density gradient, the first step is to calculate the altitude difference (h)between the shooter and target. When calculating the effective horizontal range for gravity drop on an inclined shot, the cosine of the angle is used. When calculating the vertical distance between the shooter and target, the sine of the angle is used to multiply the range:

$$h = 3000*\sin(45) = 2121\ ft$$

So for a 3000 foot shot (1000 yards) at a 45 degree look-up angle, the target is 2121 feet above the shooter. If the shot were a look down, *h* would be -2121 feet.

The next step is to use Equation 4.1 to calculate the correction factor *f*.

$$f = 1 + 1.3X10^{-5}*2121$$

$$f = 1.03$$

Finally, the correction factor of 1.03 is applied to the G7 BC of 0.233.

$$BC_{corrected} = 0.233*1.03$$

$$\boldsymbol{BC_{corrected} = 0.240}$$

Re-calculating the trajectory for the 1000 yard; 45 degree look up shot with the corrected BC results in a predicted drop of -217.0" which is 2.3" less than the -219.3" that results from ignoring the effect of air density gradient.

If the shot were a 45 degree *look down* shot, the correction factor (*f*) would be 0.97, and the predicted drop would be about 2.3" *more*.

I think many shooters have a misconception about the strength of gravity compared to aerodynamic drag when it comes to bullets. To put it into perspective, consider the 155 grain .30 caliber bullet on a level trajectory. Gravity is pulling the bullet straight down, away from the line of sight with a force of 155 grains, or 0.022 pounds. The force of aerodynamic drag that's opposing the bullet's forward motion is about 8730 grains at 2600 fps, or 1.25 pounds. So the force of aerodynamic drag is over 56 times greater than gravity. When you incline the trajectory by 20 degrees, the bullet's weight is only pulling away from the line of sight with 146 grains, and 53 grains of weight is opposing its forward motion. Those 53 grains of weight opposing the bullets forward motion is very minor compared to the 8730 grains of aerodynamic drag that the bullet is struggling to overcome. The same scale applies on a downhill shot. For a downhill shot, the bullet's forward motion is effectively being *assisted* by 53 grains, but still being opposed by 8730 grains of drag. These numbers should make it clear that aerodynamic drag is by far the largest force at work which decelerates the bullet on inclined trajectories, and working against gravity is actually a very minor effect.

Not all ballistics programs account for the effects of uphill/downhill shooting in a consistent way. Some programs simply scale the effect of gravity which results in the same effect for uphill and downhill shots. Some programs factor in the small effect of gravity working *for* the downhill shot and *against* the uphill shot. I don't know of any programs that account for the minor effect of air density gradient for uphill/downhill shots. The practical fact of the matter is that long range shots at such extreme angles are very rare, and when they happen, there are usually other important challenges like an awkward shooting position and the uncertainty of the wind conditions over such an extreme altitude split; probably with little to no wind indicators near the bullets flight path. The bottom line is that the minor effects of shooting on an incline can usually be ignored with little consequence. They are presented and addressed here for completeness, but they aren't necessarily worth sweating over.

I would like to leave the reader with the following *take away* points about uphill/downhill shooting.

- The *major effect* of uphill/downhill shooting is the effective reduction of gravity that pulls directly down from the line of sight. A bullet will drop *less* for uphill *and* downhill shots compared to a level shot. This major effect should definitely be measured and accounted for when shooting at inclination angles.
- The secondary effects of uphill/downhill shooting are:
    - The minor effect of gravity working with or against the trajectory.
    - The minor effect of the air density gradient between the shooter and target.

  The secondary effects of uphill/downhill shooting are very small in comparison to the major effect, and can be neglected for most normal shooting scenarios. In addition to being small, the secondary effects are also *offsetting*. In other words, an uphill shot will have gravity working *against* it, but it will have the thinning air working *for* it. Since both effects are very small and in opposite directions, they can usually be neglected without consequence.
- The ballistic software included with this book accounts for the effects of gravity on inclined trajectories (major and minor effect) but it *does not* account for the effect of air density gradient. In order to completely account for all the effects of inclined shots, the air density correction factor has to be applied to the bullets BC. Remember that doing so is more of an academic exercise than a practical necessity.

Chapter 5: Wind Deflection

For many shooters, this will be the most important chapter of the book. Each type of shooting; be it hunting, tactical, prone, F-class and Benchrest shooting all have their own set of problems that are more or less unique to that discipline. ***Wind deflection is a non-deterministic element, and is the most difficult challenge for all types of long range shooting.*** It would seem that this fact would compel serious shooters to learn as much as they can about the nature of wind deflection. The more you know about a problem, the more able you are to manage it. However, in spite of the importance of understanding and mitigating wind deflection, modern literature provides a surprising degree of misinformation on the subject. Because of the broad lack of detailed knowledge in regards to wind deflection, I'll do my best to present the facts in a way that can be understood by novice and advanced shooters alike. There are plenty of examples of wind deflection equations, etc., that are essentially useless for when it comes to applying their findings to real-life shooting situations. I'll avoid that. There are also plenty of examples of wind deflection being described by those who lack an accurate technical understanding of the matter to begin with. Studying either of the above cases is useless.

I hope you will find my approach effective. I believe that studying the nature of wind deflection should be the highest priority for long range shooters. It's not easy, but those who have the best understanding of the most challenging aspect of shooting are those who enjoy the greatest success.

The Philosophy of wind

This wishy-washy section title is intended to get your attention, and prepare you to open your mind and really think about the nature of wind effects on shooting. There is something fundamentally different about how you need to think about wind, versus the other variables involved in shooting.

Let's examine the variables associated with a typical long range shot in no wind conditions. You've got to measure: range and angle to target, atmospheric properties, and the sight height. You also have to know with some reasonable level of certainty what the muzzle velocity of your bullet will be, and its ballistic coefficient. All of these variables can be accounted for with readily available instruments including: a chronograph, a hand-held atmospheric measurement device and a laser rangefinder. The process is pretty straight forward: you measure all the variables, input them into a suitable ballistics program which calculates the drop under the specific set of conditions, apply the correction to the scope, and squeeze the trigger. If the precision capability of the rifle is sufficient for the target size, and all of your measurement instruments are calibrated and inputs are accurate, your shot will be a hit.

Now introduce the wind. Not a *textbook* constant 10 mph crosswind, but a real world wind complete with velocity gradient, direction changes, eddies, pick-ups, let-offs, vertical components, etc. If you think you are going to measure the wind, calculate the deflection, apply the sight correction, and easily hit your target at long range, then you are setting yourself up for disappointment. The bottom line is that wind is not like any other variable in shooting. You can't take a measurement of wind speed and direction at one point and assume it applies to the entire trajectory. Wind is not constant like gravity, or predictable like aerodynamic drag. The unpredictability and uncertainty inherent to wind is the root of the problem. We can't apply our classical *measure and account for* approach to the wind deflection problem. Wind is air in motion; a fluid. Fluids have a nasty habit of being chaotic and difficult to predict in general. The problem that so many long range shooters have with wind is they attempt to simply *measure and account for* its effects, without understanding that their measurement is only valid at one point on the trajectory, and may not apply downrange. There's also the time dimension. Even if you judge the exact wind field accurately at any given moment, by the time you've calculated the effect and adjusted the scope to account for it, the condition has changed and your solution is invalid!

Clearly an alternative approach is required to deal with wind deflection. We can't count on the old *measure and account for* approach, so what do we do? Well, unfortunately there is no absolute *magic* solution that enables you to hit targets reliably in any wind condition. I wish there were, but until laser Doppler velocimetry units are introduced to the sporting arms industry, there is no absolute answer. (In 2007 Lockheed Martin began development of a DARPA funded electro-optic system called 'One Shot' which uses lasers to measure the complete wind field along a line of sight and provide a corrected fire control solution. Needless to say, this technology will be confined to special military units for many years). Since there will be no magic solution to the wind deflection problem for most shooters in the near future, we're left with a need to overcome the problem thru actually understanding its fundamental nature.

The approach is quite simple, here it is: ***Since you can't reliably measure and account for wind deflection, the best you can do is MINIMIZE its***

uncertainty and its effects. This is the best technical approach to dealing with the wind problem. There are two major things you can do to minimize the effects of wind:

1. Of course you can practice your wind reading skills; by observing the cause and effect relationship between wind conditions and bullet deflection.
2. Also, if you can obtain a real insight of how wind deflection works, you can make smart decisions about your equipment (rifle and bullet) that result in superior ballistics in the form of minimal wind deflection.

The first item (actually *practicing* wind reading skills) is the best way to improve your shooting in the wind. However, this requires access to a long range facility or field, time and money involved with the shooting, and years of practice to master. Actually, no-one ever really *masters* wind reading, it's a matter of continuing improvement. There are certain practice drills and things you can do to improve your familiarity with wind conditions. For example, I have a Kestrel 4000 weather probe (wind meter) that I carry with me while walking the dog. Periodically, I'll stop, look around at the indicators (grass, leaves, etc.) and try to guess the wind speed. Then I look at the wind meter and see how close I am. When I first started this drill, I was guessing within +/- 2 to 3 mph of the actual wind speed. After a couple seasons of this, I'm able to estimate wind speed to within +/- 1 mph (usually).

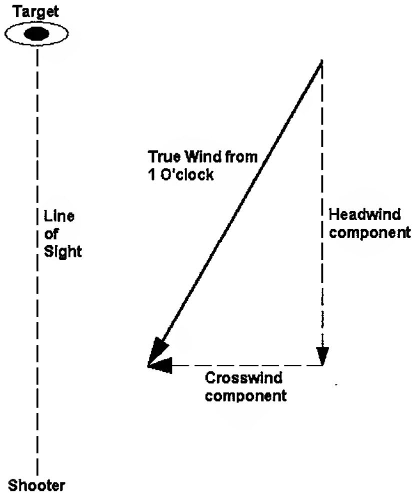
If you're a long range target shooter, you rely heavily on large range flags as wind indicators. In this case, it would be valuable practice to stand near such a flag and play the guessing game. In this way, you can calibrate your wind reading skills to the indicators that are available to you during the match.

The second item (choose equipment with superior ballistics) is a far more instant and certain way to boost your resistance to the effects of wind. ***Regardless of your level of skill in reading wind, choosing equipment with superior ballistics will improve your chances of success in long range shooting.*** This is an unarguable fact. Think of it this way: if you and your buddy are equally good at reading wind, but your bullets are less affected by the wind, you will be more accurate while shooting in the wind. Likewise, if your buddy is better than you at reading wind, but your bullets are less affected by the wind, you may be able to make up for the lack of wind reading skill by having the better ballistics. As with everything, there are degrees. You can't make up for a complete lack of wind reading skills with good ballistics. Likewise, if you're the best wind reader out there, you could always be more accurate with better ballistics. A successful long range shooter strives for balance among the many skills and assets involved in shooting. By constantly practicing wind reading skills AND making smart decisions about ballistics, one can build a surprising tolerance to the effects of wind.

The remainder of this chapter will be spent presenting the relevant scientific facts of wind deflection. You already have the philosophy of *what* to do, which is: minimize the effects of wind deflection. The following information in this chapter will enable you to actually do it thru superior ballistics. Remember, my intent is not to present extensive mathematical rigor. My intent is to communicate the relevant and actionable facts that will allow you to minimize the uncertainty of wind and its effects.

Cross wind component

For practical long range shooting, we are only concerned with the component of wind that's blowing across the line of sight. In other words, direct head winds and tail winds have a negligible effect on the bullet's point of impact, but a 3 O'clock or 9 O'clock crosswind has a full value effect. In the real world, a wind condition is hardly ever a perfect head or tail, or cross wind.



True Wind Direction	Crosswind factor
12 or 6 O'clock	0.00
1, 5, 7 or11 O'clock	0.50
2, 4, 8, or 10 O'clock	0.87
3 or 9 O'clock	1.00

Figure 5.1. Crosswind factors

Usually, the wind is coming from an intermediate direction where one component of the wind speed can be directed *along* the line of sight, and the other part is directed *across* the line of sight. The component of the wind that's directed across the line of sight is called the *cross wind component*, and it's the component of wind speed that is of interest to us as long range shooters. When you enter wind speed and direction into a ballistics program, the first thing the computer does with those inputs is to convert that combination into the crosswind component. Figure 5.1 is an illustration of crosswind factors for the major clock positions. For example, if there's a 10 mph wind blowing from 1 O'clock, and you need to know the crosswind component, you multiply the full value wind (10 mph in this case) by the crosswind factor for 1 O'clock, which is 0.50. The result is 5 mph. We would say that *the crosswind component for a 10 mph wind from 1 O'clock is 5 mph.* If the 10 mph wind were from 2 O'clock, we would say *the crosswind component of a 10 mph wind from 2 O'clock is 8.7 mph* (10 mph times 0.87).

When doing calculations involving wind deflection, only the *crosswind component* matters. In some cases, you can have vertical wind components, which are winds blowing up thru, or down thru the bullets trajectory. These vertical wind currents are usually not as strong as the horizontal wind components, but you still need to take the vertical wind into consideration.

Lag Time

Lag time is a fundamental concept to the understanding of wind deflection. In words, lag time is the difference between the actual time of flight, and the time of flight in a vacuum, that is, with no air resistance. For example, consider a bullet fired at 3000 fps at a target 1000 yards away. The *vacuum* time of flight is 1.0 seconds (bullet travels 3000 feet at 3000 feet per second because there is no drag to slow the bullet in a vacuum). In reality, aerodynamic drag causes the bullet to slow down during its flight, and so the actual time of flight to 1000 yards is closer to 1.5 seconds. In this example, the lag time is:

1.5 seconds – 1.0 seconds = 0.5 seconds.

In general equation form:

$$T_{lag} = tof - tof_{vac}$$

Equation 5.1

Where:
T_{lag} = Lag Time (seconds)
tof = Actual bullet time of flight (seconds)
tof_{vac} = Theoretical vacuum time of flight (seconds)

Actual wind deflection is directly proportional to lag time and crosswind speed. In other words, if you double lag time, you double wind deflection for the same wind condition. In words, wind deflection is simply lag time times crosswind speed. Here is the equation for wind deflection in terms of lag time:

$$W_d = W_s * T_{lag}$$

Where:
Wd = wind deflection (feet)
Ws = crosswind speed (feet per second)
T_{lag} = Lag time (seconds)

Since wind speed is usually measured in miles per hour, and wind deflection in inches, the following equation includes the conversion factor to allow convenient units.

$$W_d = 17.6 * W_s * T_{lag}$$

Equation 5.2

Where:

Wd = wind deflection (inches)
Ws = crosswind speed (mph)
T_{lag} = Lag time (seconds)

The above equations are useful for understanding how to calculate wind deflection, but they're not of much practical use. Think about it, you need the actual time of flight to calculate lag time, and you need a ballistics program to get time of flight. If you have a ballistics program, you can just use it to calculate wind deflection directly! I invite the interested reader to compare the wind equation to the output of a ballistics program to prove to yourself that the lag time and wind speed are related exactly as described in that simple equation.

The derivation of the wind deflection equation is very long and complex. The lag time equation is one of those fortunate simplifications in physics that captures a very complex mechanism in a simple, elegant equation. For the purposes of this book, we won't be exploring these kinds of details. For our purposes, the main point to take away from the wind deflection equation is that: wind deflection is directly related to both *lag time* and *crosswind speed.* We don't have any control over the crosswind speed, and we have limited ability to even measure it, that's the problem. *What that means to us is*: *in order to minimize wind deflection, you have to focus on the thing that you can affect, which is lag time.* In other words, what the wind equation is telling us is: ***in order to minimize wind deflection, you have to minimize lag time.***

Now you know why lag time is so important. Remember the significance of danger space to bullet drop? In the same way that danger space is the measure of ballistic *quality* for drop, lag time is the measure of ballistic *quality* for wind drift. More lag time means more wind drift and vice-versa. Lag time encompasses all of the things that make a bullet more susceptible to wind deflection including bullet BC, muzzle velocity, range, and atmospheric conditions.

Among all the things that affect lag time, there are two key items that are of high interest: Ballistic coefficient and muzzle velocity. The reason these two items are *key* is because they're the things that we can *control.* Range to target and atmospheric conditions also affect lag time, but we don't have any control over them.

Here's a little review of the important facts, just to highlight where we stand:

- Wind deflection is not a deterministic element and cannot be *measured and accounted for* like most other variables in long range shooting.
- The best way to *deal with* the uncertainty of wind deflection is to minimize its uncertainty and its effects.
- Lag time is the key measure of ballistic *quality* for wind deflection.
- In order to minimize wind deflection, focus on minimizing lag time.

- Many factors combine to influence lag time. We only have control over several key factors including ballistic coefficient and muzzle velocity.

The following sections will go into detail on how lag time is affected by each of these key factors. Understanding these ideas will help in the decision making process when considering what compromises to make. Shooters are often confused by the effects of velocity and BC on wind deflection. Many believe that a bullet with a lower BC going extremely fast will have less wind deflection because the wind *doesn't have time* to deflect the bullet. Is that really true? The following sections will answer that question.

How Ballistic Coefficient affects lag time

In general, bullets with higher BCs have less lag time.

Let's consider three different bullets: a .224 caliber 60 grain bullet, a 6.5mm 100 grain bullet, and a 155 grain 30 caliber bullet. These are 'hypothetical bullets', invented to allow a clear example. They represent medium weights for the calibers, and are scaled copies of each other[3]. In other words, all three bullets have the same G7 form factor which we'll assume is 1.0 in this example. This gives the bullets G7 BCs equal to their sectional density[4]. The G7 BCs are: 0.171, 0.205, and 0.233 respectively. If each of these bullets is fired at the same muzzle velocity, at the same range, the lag time will be greatest for the lowest BC bullet and vice-versa. Figure 5.2 shows the total time of flight, vacuum time of flight and lag time for each of these three 'hypothetical bullets' over 600 yards. Notice that all three bullets have the same vacuum time of flight. That's because they were all fired at the same muzzle velocity, over the same distance. 3000 fps for 600 yards (1800 feet) is 1800/3000 = 0.600 seconds. Now, since the bullets have different BCs due to their different calibers and weights, they all lose velocity at different rates. High BC bullets maintain velocity better than low BC bullets. Since the high BC bullets maintain velocity better, their total time of flight is less, which means their lag time is less. In this conceptual example, the 155 grain 30 caliber bullet has 0.08 seconds less lag time than the 60 grain .224 caliber bullet. That means that the .30 caliber bullet is 32% less wind sensitive than the .224 caliber bullet *for all wind conditions at 600 yards*. For the case of a 10 mph crosswind, the .224 caliber bullet would have 42 inches of wind deflection, while the .30 caliber bullet would only have 28 inches of wind deflection. At a different distance, the lag times are all different, and so the relative proportions change. If one bullet has a lag time advantage at a particular range, the advantage will be greater at longer ranges[5].

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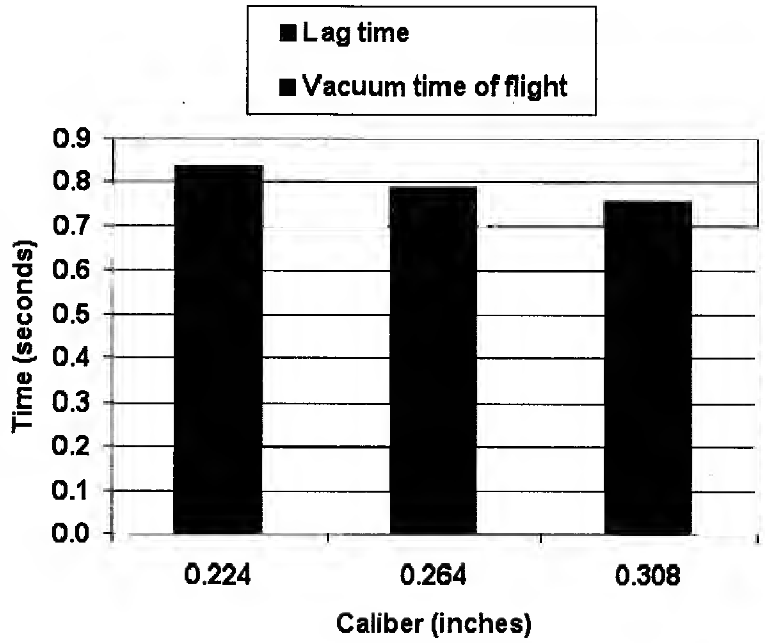
[3] See Chapter 11 for details on scaling bullets to various calibers.

[4] Chapter 2 contains details of how to calculate BC from form factor and sectional density.

[5] This statement is true for bullets fired with equal muzzle velocity.



Caliber/G7BC	Total tof	Vacuum tof	Lag time
0.224/0.171	0.838	0.600	0.238
0.264/0.205	0.786	0.600	0.186
0.308/0.233	0.758	0.600	0.158

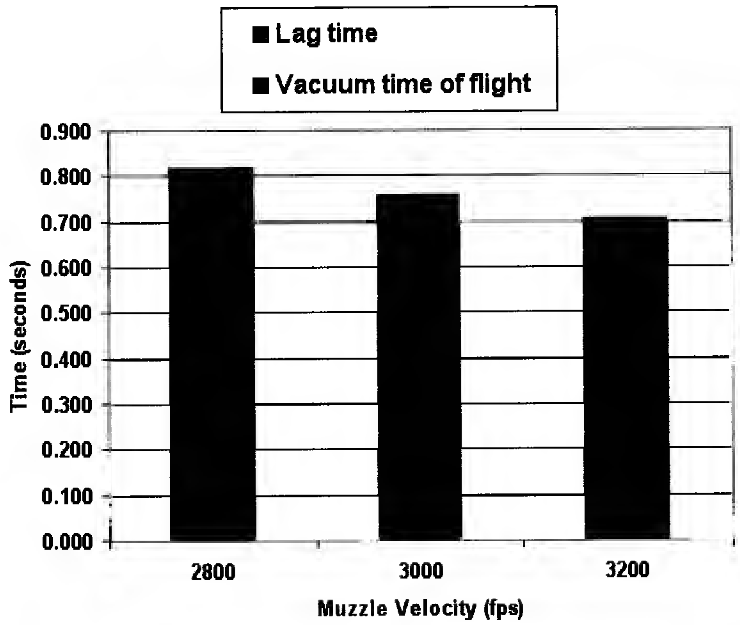
Figure 5.2. Each round is fired at 3000 fps to 600 yards, so they all have the same vacuum tof. The plot shows that the smaller calibers with the lower BC's have greater lag time.

Granted, these are 'hypothetical bullets' used in this example but they illustrate the trend well. Sometimes it's easier to work with simplified models in order to see the governing physics behind a complex problem. Just make sure the model isn't *too* simplified.

How muzzle velocity affects lag time

In general, higher muzzle velocity decreases lag time.

To investigate this idea, let's only consider the .30 caliber, 155 grain bullet used in the conceptual example above. I choose this particular bullet because it's very close to an actual bullet. The .308 155 grain Lapua Scenar has a G7 form factor which is very close to 1.0 for all practical purposes, and has a G7 BC of 0.236. As mentioned above, the conceptual bullet has a G7BC of 0.233. Figure 5.3 shows the lag time trend as this bullet is fired at various muzzle velocities over a distance of 600 yards.



Muzzle Velocity	Total tof	Vacuum tof	Lag time
2800 fps	0.819	0.643	0.176
3000 fps	0.758	0.600	0.158
3200 fps	0.705	0.563	0.142

Figure 5.3. .30 caliber, 155 grain bullet, G7 BC = 0.233 fired at 600 yards. Total tof, vacuum tof, and lag time for 3 different muzzle velocities.

There's some interesting stuff going on in this Figure. It's clear that higher muzzle velocity results in less vacuum time of flight, and less lag time. However, the interesting thing is that vacuum tof decreases more than lag time as muzzle velocity goes up. As muzzle velocity increases from 2800 fps to 3200 fps, vacuum tof decreases by 0.080 seconds, while lag time only decreases by 0.034 seconds. Obviously, the drop in vacuum time of flight is directly proportional to increases in muzzle velocity, but does that same relationship hold for lag time? Take a look at the bar graph in Figure 5.3. Notice how the high velocity bars seem *compressed.* That's effectively what you're doing when you go faster: *compressing the time* it takes to cover a distance. But if you look at the numbers, you can see that the lag time is not exactly a constant fraction of the total tof. For example, at low speed (2800 fps), the lag time is: 0.176/0.819 = 22% of the total tof. At high speed (3200 fps), the lag time is only: 0.142/0.705 = 20% of the total tof. Why would the *lag time fraction* change at all when muzzle velocity changes, and why is it less at higher speeds? The answer to that question is found in the supersonic drag profile. Remember the Mach vs Cd plots back in Chapter 2? ***The drag coefficient is lower at higher speeds, and that's why there's a lower lag time fraction for higher velocity flight.*** Of course the *force* of drag is greater at higher speeds due to the higher dynamic pressure, but since the *drag* *coefficient* is lower, the bullet has a smaller *lag time fraction* at higher speeds, which results in a slightly lower lag time fraction.

In conclusion, there are two reasons why lag time is smaller for bullets fired at higher muzzle velocities:

1. Increasing muzzle velocity effectively *compresses* the timeline for the flight. Vacuum tof and lag time are both compressed. This is the primary cause of lag time reduction for elevated muzzle velocities.
2. Increasing muzzle velocity also reduces the *lag time fraction* for the flight due to the lower drag coefficient at higher supersonic speeds. This effect is considered secondary in comparison to the previous one.

Reality: The combined effects of BC and muzzle velocity on lag time

The previous two sections looked at the effects of BC and muzzle velocity on lag time. These two effects were studied in isolation so that the individual mechanisms could be understood before trying to put everything together.

My 8 year old step son is working on his first book report. In order to write a book report, you need to have mastered the fundamentals of reading, comprehension and writing, each of which is mastered independently before they're put together. Many ideas in exterior ballistics, including the present discussion of lag time and wind deflection, are similar to a book report. You have to isolate and master an understanding of the individual parts before you can assemble them in a meaningful way. This section should be considered the *book report* on lag time.

In reality, you're never just deciding between velocity and BC in isolation, the two are tied to each other. Typically, choosing a higher BC bullet means more weight, and that means lower muzzle velocity. In order to look at both BC and velocity effects, we need some way of relating them. How much slower should we expect a heavier bullet to be from a given cartridge? There's a simple energy balance technique that can be used to approximate an answer to this question. The technique is based on the idea of matching kinetic energy at the muzzle. For example, consider the .308 Winchester cartridge with 155 grain bullets. If you can get 3000 fps out of this combination, what speed could you get with 175 grain bullets from the same cartridge at the same pressure level?

The following equation can be used to predict the velocity of a different weight bullet *of the same caliber, from the same cartridge, at the same pressure.*

$$V_2 = V_1\sqrt{\frac{W_1}{W_2}}$$

Equation 5.3

Where:

V_2 is the velocity of the bullet you're looking for in fps
V_1 is the velocity of the bullet you know in fps

W_2 is the weight of the bullet you're looking for in grains
W_1 is the weight of the bullet you know in grains

For the example above, Equation 5.3 looks like this:

$$V_2 = 3000\sqrt{\frac{155}{175}}$$

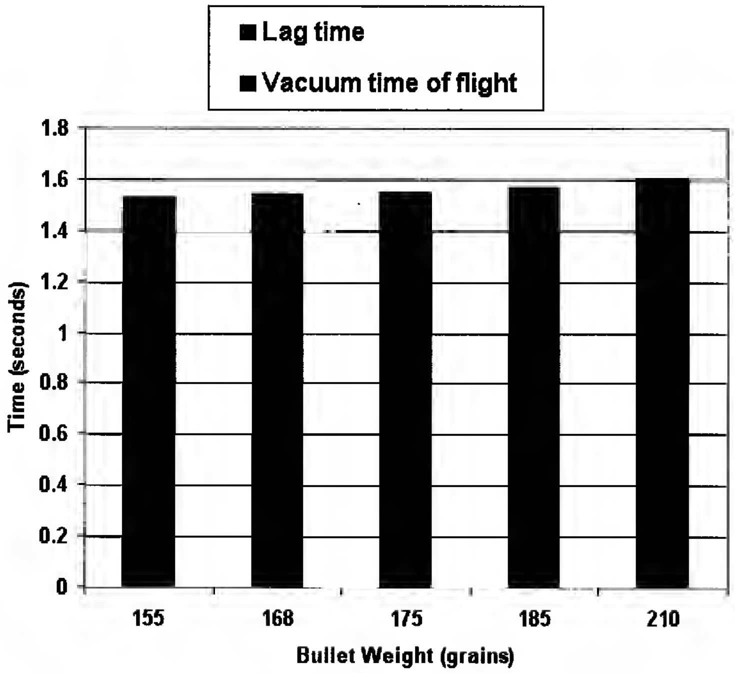
$$V_2 = 2823\ fps$$

This tells us that if we can achieve 3000 fps with the 155, then we can expect 2823 fps with a 175 when loaded to the same pressure.

This technique can be used to approximate the velocities that are possible with various weight bullets from a given cartridge. The assumption is that the kinetic energy at the muzzle is constant. This implies that the average chamber pressure is also matched. In other words, if the 3000 fps load was hot for the 155 grain bullet, then the 2823 fps load will also be hot for the 175 grain bullet. The approximation maps well to real world data, but you should be careful to remember that it's just an approximation. You may find instances where the numbers don't map well according to the equation, especially for bullets of various brands. Sometimes the nominal bullet diameter varies among brands, and this would affect the internal ballistics in a way not predicted by the equation. Furthermore, powders with slower burn rates are typically used for heavier bullets, which changes the character of the chamber pressure and can compromise the accuracy of the velocity prediction technique. Even with such practical short falls of this velocity prediction technique, it will suffice for our current study of lag time trends. Now that we have a way to predict the BC vs muzzle velocity trade-off, let's investigate the effects on lag time.

For this study, we'll first put the .308 Winchester under the microscope and examine the possible combinations of BC and velocity, and the lag time associated with each. In order to simplify things, we'll concentrate on a line of bullets that has a pretty constant form factor, the Berger VLDs. These bullets are available in .30 caliber in the following weights: 155 grain, 168 grain, 175 grain, 185 grain, 190 grain and 210 grain. The 155 thru 175 grain bullets are essentially all the same shape. The 185 thru 210 grain bullets have a longer boat-tail (which reduces base drag), but a longer overall length (which increases skin friction drag). In the end, this entire line of VLD bullets has a relatively constant form factor, averaging right around 1.0. For the purposes of this study, we'll consider them all to have a form factor of 1.0. After all, this is a study of lag time, not form factor. Note that the same study could be done on any line of bullets having a constant form factor, be it Nosler Ballistic Tips, Sierra Match Kings, Hornady A-max, Lapua Scenars, etc. Ambitious readers may be compelled to repeat this analysis using the actual form factors for each bullet, which are found in the back of this book.

For this analysis, I chose to model a rather *stiff* load for the .308 Winchester, which is popular among Palma shooters. Competitors are able to average around 3000 fps with the 155 grain bullets which are mandated for international Palma and Fullbore shooting. This represents a near maximum load in terms of chamber pressure for the .308 Winchester with a 30" barrel. All of the analysis in the following example will be based on this level of kinetic energy (chamber pressure) for the .308 Winchester, which is 3095 ft-lb. Figure 5.4 illustrates how the lag time is affected by changing bullet weight in the .308 Winchester cartridge. Here are the major conclusions to be drawn from this analysis of the .308 Winchester in Figure 5.4:



Weight	G7BC	MV (fps)	Total tof	Vac tof	Lag time
155 grain	0.233	3000	1.528	1.000	0.528
168 grain	0.253	2882	1.543	1.041	0.502
175 grain	0.263	2824	1.552	1.062	0.489
185 grain	0.279	2746	1.566	1.092	0.473
210 grain	0.316	2578	1.604	1.164	0.440

Figure 5.4. Lag time at 1000 yards for various weight bullets, fired at constant muzzle energy.

Going from light to heavy:

1. The muzzle velocity decreases. This is a natural consequence of having to reduce the powder charge to keep the pressure constant.

2. The *total time of flight* increases due to the depressed muzzle velocity of the heavier bullets.
3. The *vacuum time* of flight increases, also due to the depressed muzzle velocity of the heavier bullets.
4. ***The lag time decreases due to the increased BC of the heavier bullets.***

Point number 4 is the major point, and the most valuable conclusion of this analysis. It says that even though the heavier bullets start out at a slower speed and has a longer total time of flight, the higher BC more than makes up for it, resulting in a net advantage for the slower heavier bullet. In other words, ***given a constant level of initial energy, the heavier bullet ends up with less lag time because the increased BC reduces lag time more than the velocity depression increases it.***

In conclusion, minimum lag time will always be realized by the highest BC (heaviest) bullet available in the caliber. There is an exception to this rule, and it's apparent if you remember the assumptions that this analysis was based on. In particular, the assumption that the form factors are the same for all the bullets under consideration may not always hold.

For example, the conclusion holds if you're considering only Berger VLDs, or only Sierra MatchKings. In this case, all the bullets will have essentially the same form factor. However, if you're considering a lightweight bullet with a good form factor versus a heavyweight bullet with a bad form factor, it's possible for their BCs to be nearly equal. In that case, the advantage goes to the lighter bullet because it will have a higher muzzle velocity and a BC equal to the heavier bullet. *If the BCs are the same, of course the faster bullet will have less lag time.*

The preceding analysis may beg the following question from some readers. *Is it possible to fire the lower BC(lighter) bullets fast enough that they have less lag time than the higher BC (heavier) bullet, and how much faster would the lighter bullets have to be fired to accomplish that?* The short answer is: Yes it's possible, but the lighter bullets would require a *great deal* more speed. As the preceding sections showed, it takes a lot of extra muzzle velocity to accomplish the same lag time reduction as a small increase in BC. The following analysis is the *long answer* to the question.

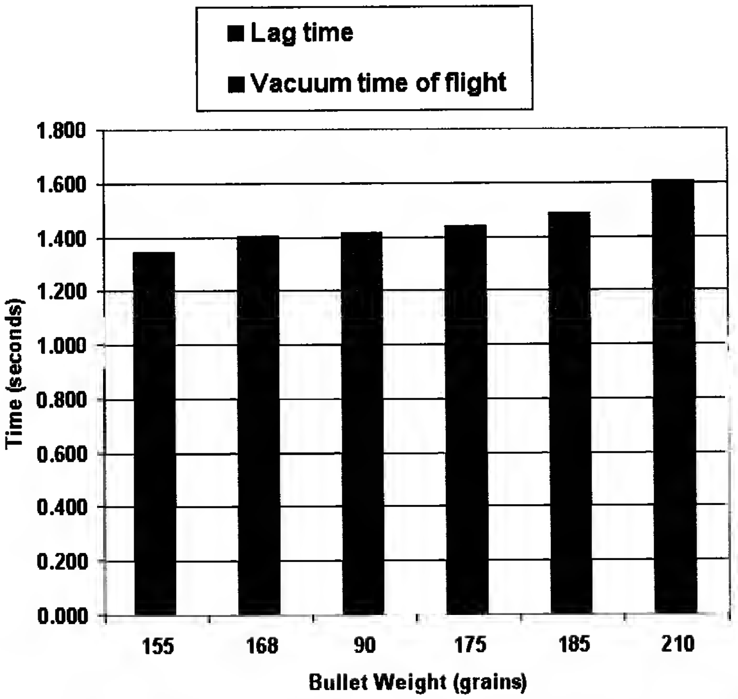
In this example, we'll consider the .308 Winchester with the 210 grain VLD having 0.440 seconds of lag time at 1000 yards as the combination to beat. We'll see how fast the other .308 caliber bullets have to be fired in order to match that lag time. We'll also consider a smaller caliber, .224, with a 90 grain bullet which is the heaviest VLD made in that caliber. We'll continue with our assumption that all the bullets, being VLDs, have about the same form factor. The point is to see what muzzle velocity is required from each bullet to match the lag time of the .308 Winchester with 210 grain VLDs at 2578 fps muzzle velocity. Figure 5.5 summarizes the results.

In Figure 5.5, we see the expected trend that the lighter bullets require more velocity and shorter total time of flight in order to match the lag time of the high BC bullet. Take a look at the velocity required from the 155 grain bullet to match the lag time of the 210 grain bullet: 3330 fps. That's not possible with a normal, safe .308 Winchester. The 2578 fps of the 210 grain bullet, however, is completely attainable at safe pressure levels. Also note that the kinetic energy at the muzzle is over 700 ft-lb greater for the 155 grain bullet.

Take a look at how the 90 grain .224 bullet stacks up against the .30 caliber bullets. The little 90 grainer requires 3080 fps to achieve the 0.440 seconds of lag time, which is difficult to achieve for that bullet in standard chamberings. Putting enough powder behind that little bullet to make it go that fast would certainly result in an accelerated rate of barrel wear.

I'd also like to point out that the required muzzle velocity of the 90 grain bullet is in between the velocity of the 168 grain, and 175 grain .30 caliber bullets, *as is the BC of the 90 grain bullet.* The significance of this fact is that it demonstrates that BC and muzzle velocity alone will determine what the lag time of a bullets flight will be. Even though the 90 grain bullet is a smaller caliber, weighs much less, and has much lower KE at the muzzle, the lag time is completely in alignment with the bullet's BC. Some shooters believe that there is more to calculating wind deflection than BC and muzzle velocity. *There isn't!* If two bullets have the same BC, and are fired at the same velocity, it doesn't matter if one is heavier, or is a different caliber, or has a different form factor. It's possible to have all three factors (caliber, weight, and form factor) be different, yet combine to produce the same BC. If the BC and muzzle velocity are equal, the lag time and resulting wind deflection will also be equal, period. I will re-emphasize this point: ***Everything about the entire trajectories will be identical if the BC and muzzle velocity are the same.***

It's easy to understand how this fact can be hard to accept, and why there's so much *smoke and mirrors* surrounding the subject of wind deflection. First of all, there's the form factor dependence on velocity issue, covered in Chapter 2 (it's the G1 vs G7 thing). Also, as we know, there is rarely a steady cross-wind in the real world in which to perform precise comparisons of wind deflection. Despite these things that muddy the waters, be assured that: ***for a given range and atmospheric condition, lag time and wind deflection depend completely on muzzle velocity and BC.***



Bullet Weight	G7BC	MV (fps)	KE	Total tof	Vac tof	Lag time
155 gr	0.233	3330	3813	1.341	0.901	0.440
168 gr	0.253	3113	3611	1.404	0.964	0.440
90 gr (.224 cal)	0.256	3080	1894	1.414	0.974	0.440
175 gr	0.263	3005	3505	1.439	0.998	0.440
185 gr	0.279	2870	3378	1.485	1.046	0.440
210 gr	0.316	2578	3096	1.604	1.164	0.440

Figure 5.5.The lower BC bullets need more muzzle velocity to match the lag time of higher BC bullets *regardless of caliber and bullet weight.*

Here is a list of important conclusions from this section on wind deflection:

1. Since wind deflection cannot be exactly predicted, the best way to manage the problem is to ***minimize it.***
2. Lag time is a property of the bullet's flight that is directly related to wind deflection. By minimizing lag time, you also minimize wind deflection.
3. Lag time is affected by two major things that the shooter has control over: BC and muzzle velocity.
4. Increasing BC reduces lag time for a given muzzle velocity.
5. Increasing muzzle velocity reduces lag time for a given BC.

6. For a given level of muzzle energy (in a given caliber) the best combination of BC and muzzle velocity is to use the heaviest bullet (highest BC) available, even if it has the slowest muzzle velocity.
7. It is possible for a low BC bullet to have less lag time, and less wind drift than a higher BC bullet, but the lower BC bullet needs to be going a lot faster to accomplish it.
8. Muzzle velocity and BC alone determine the wind sensitivity of a bullet.

Near Wind and Far Wind

Wind conditions in the real world vary so much between the muzzle and target, it's impossible to know the exact speed and direction of the wind along all points of the trajectory. So since you can't know all the wind all the time, it's critical to know what wind is most important to pay attention to. One very common debate among long range shooters is about this exact question. Does the wind that's close to the shooter (near wind) have more influence over the total wind deflection, or is the wind at the target (far wind) more important? The following two subsections will explain the gist of the reasoning behind each argument.

Argument for near wind

Near wind is more important because it's the wind that affects the bullet earliest in its flight. The bullet will spend the rest of its flight on a deviated path according to how the near wind affected it. On the contrary, the far wind doesn't affect the bullet until its closer to the target, and by then, the bullet's flight is almost over.

Argument for far wind

Far wind is more important because the bullet is going slower when it's far downrange, and is more susceptible to the effects of wind. The bullet spends more time covering the last half of its flight than the first half, so the wind has more time to act on, and deflect the bullet. When the bullet is near the shooter, it's going so fast that the wind barely affects it at all.

I know several very reputable proponents of each of the above arguments, which suggests that there is no easy answer to the debate. Let's go a little deeper and explore the details of this problem.

First of all, we have to remember that we're interested in the real world effects of wind, not just what some textbooks might calculate, after making some simplifying assumptions. Be that as it may, it's still worthwhile to examine the textbook answer first, if nothing else, so that we have a starting point.

The textbook answer says that the near wind is more important than far wind, for the reason given in the argument above. For a given wind speed, the *total deflection* is more dependent on how the bullet is affected early in its flight. For example, consider a bullet that's fired into a cross wind that results in a deflection of 1" at 100 yards. Now let it fly 900 more yards in zero wind. The total deflection will be about 10" at 1000 yards. Now fire the same bullet thru 900 yards of no wind, then the last 100 yards with the crosswind. The bullet may drift more than 1" in that last 100 yards because it is going slower. However, it will drift a lot less than 10". This example clearly illustrates the *textbook* reasoning that suggests near wind is more important than far wind.

There are some problems with the *textbook* argument (no surprise!). First of all, the *constant* wind used in the example never happens. Usually, the wind speed and direction are quite variable along the bullet's trajectory. Sometimes the wind is stronger downrange and/or has more of a crosswind component and these effects would make the bullet more susceptible to deflection downrange. Second of all, there is another important real world dimension of wind behavior that we haven't talked about yet: *wind gradient*. *Wind gradient* is the variation of wind speed with height above the ground. The wind speed right on the ground, in the grass, is essentially zero. One foot above the grass/vegetation there is a breeze, and the higher you go, the stronger the wind gets (to a point). The wind is therefore several times faster at a height of 10 to 20 feet above the ground (the top of a bullet's arc) than it is right on the ground where the shooter is firing from. ***The textbook answer to the near wind/far wind question completely ignores the presence of 'wind gradient'***, which is one reason why the theory doesn't always hold in the field.

So if the near wind argument isn't valid, then the far wind must be more important right? Not so fast! Just because the bullet is going ½ as fast at the target doesn't mean it's twice as sensitive to wind (see previous discussion about lag time). The bullet will be slightly more sensitive to wind at lower speeds, but not as much as is commonly thought.

So what's the answer! If it's not near wind, and it's not far wind, it must be the wind halfway between the shooter and target that's most important, right? Midway from shooter to target is where the bullet is highest above ground, and subjected to the strongest wind speeds, so it must be the midrange wind that's most important, right? Strike three!

Alright, if it's not near wind, far wind, or mid-range wind, then what wind is most important!? The real answer is: it depends. It depends mostly on the unique features of the terrain over which you're shooting.

This near wind/far wind debate is a perfect illustration of why wind is such a unique consideration for long range shooters. We get into the habit of measuring and correcting for all the variables, so we try to apply the same technique for wind. We think there must be some general, governing rules of thumb that can be applied to systematically dope the wind in every situation, but it's not so. In fact, the blanket application of any one policy, be it the near wind or far wind, can be worse than no policy at all. The right approach is to examine the range, and observe the unique features of the landscape and make a decision based on the information that's most important for that place.

I'll tell you a story about how this lesson was driven home for me. I'd been studying ballistics and the effects of wind, and was aware of the compelling textbook argument for near wind being more important. In 2008, I traveled to Winnequah gun club in Lodi, Wisconsin for the Midwest Palma Championship. This would be my first time shooting at this range, and the competition for the 4 day tournament was tough. Palma tournaments like this where everyone has to shoot the .308 Winchester are usually won by the best wind readers. Not being familiar with the range, I knew I would have to pay close attention early on to learn the unique features of this range quickly. As you look downrange at the targets on the Lodi range, there is one special feature that sticks out more than anything else. A valley spills onto the range from the right, about 300 yards in front of the targets. There are no trees in this valley to slow the wind down like there is everywhere else along the range. Also, as the bullet flies over the valley, it's farther above the ground than anywhere else in its trajectory, which is another reason why it would encounter higher speed wind at that point. I decided before my first shot that I would pay closest attention to the flags in and near that valley than anywhere else, even though the textbook answer suggests paying closer attention to the flags closest to the shooter. I stuck to my plan from the first to the last shot of that tournament, and won the championship. Many times in the 4 days, shooters would come off the line shaking their head, mumbling stuff about the unreadable wind. Things can get quite confusing if you're watching the wrong indicators and trying to correlate them to what you're seeing at the target.

The above example is one case that illustrates the correct wind policy to apply in the field. The policy is flexibility. When judging the effects of the wind, consider the major terrain features and how they will affect the wind patterns along your line of sight. If your initial assessment of the important indicators on a range turns out to correlate poorly to what's happening on the target, look for other indicators, and be ready to change your assessment until you find the true indicators. Of course, long range hunters and tactical shooters don't often get more than one shot, so the process of *guess and check* isn't really practical. In the case where you only have one shot, you simply have to rely on experience and your own critical assessment of the situation. If you don't have any experience, you won't get it from this or any other book! It's something you simply have to practice, paying close attention to the causes and effects, and remembering the lessons for next time. A journal or log book can help those of us with imperfect memories.

The Mechanism of Wind Deflection

So far, this chapter on wind deflection has kept with the spirit of the book, meaning it has presented actionable information or information that can be used to research and make practical decisions about your shooting equipment and loads. This section is a slight diversion from that theme. It's not necessary to know exactly *how* wind acts to deflect a bullet. We just care about the important factors that influence *how much* the bullets are deflected, and how to minimize the deflection. Since wind deflection is such an important feature of long range shooting, and since it's also widely misunderstood, I decided to include this section explaining exactly *how* the wind deflects our bullets. For those who are really only interested in the actionable information in this book, you can consider this section optional reading. I included it for the more academically curious readers. My explanations will be verbal and visual, leaving the equations out of it.

The most common myth about how wind deflects a bullet is that: the wind blows on the side of the bullet, like a balloon, and pushes it off course. This description of wind deflection is simple and intuitive, but very wrong.

In order to really understand what a bullet does when fired into a crosswind, it helps to be familiar with the definition of stability. There is a later chapter dedicated to stability, but for now, I'll give the basic definition so we can proceed. *Stability for spin stabilized projectiles is when the bullet is able to maintain point forward flight.* This definition is not complete, but it will do for our purposes. The important part of this definition is *point forward flight.* This does not mean the nose is pointed straight along the line of sight. *It means that the nose is always pointed straight into the oncoming air flow like a weather vane.* It's easy to imagine the weather vane effect if you've ever shot an arrow into a strong crosswind. Even though arrows are stabilized with fletching, and bullets are stabilized with spin, they both point their nose into the on-coming air flow when they're in stable flight. Keeping the nose pointed into the wind is the fundamental definition of stability, whether it's achieved with fins or with spin.

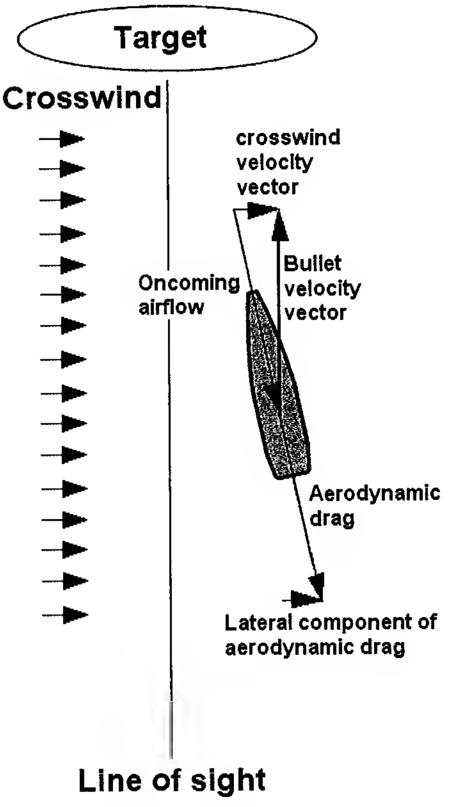


Figure 5.6. The mechanism of wind deflection

In a no-wind situation, having the bullet pointed straight into the oncoming air flow is the same as having the bullet pointed straight along the line of sight. However, that's not true if you introduce a crosswind. If the air that the bullet is flying thru is moving *sideways*, the bullet points its nose straight into the oncoming air flow like a weather vane. Now, *the axis of the bullet is no longer aligned with the line of sight.* Figure 5.6 shows an exaggerated sketch of the bullet pointing its nose into the oncoming air flow, and flying at an angle to the line of sight. Again, the angle is exaggerated in the figure.

In reality, the bullet only makes a very small angle with the line of sight, usually less than ½ of a degree. As the bullet flies at an angle to the line of sight, the force of aerodynamic drag is acting in line with the airflow, which is in-line with the bullet axis, but which is *not in line* with the line of sight. The result is that a small component of the aerodynamic drag on the bullet is directed *across* the line of sight. This small lateral component of drag is what accelerates the bullet away from the line of sight. The trigonometry for figuring out the angle of bullet flight is fairly simple. If the bullet is flying at 3000 fps, and the crosswind is 14.67 fps (10 mph), then the bullet will fly at a: atan(14.67/3000) = 0.28 degree angle (atan(x) means the angle whose tangent is x). You can figure out the magnitude of the lateral component of drag in the same way. For example, if there were 1.5 total pounds of drag applied back along the bullet's axis, the lateral portion of that force is: 14.67/3000, or 0.489%. So in this example, there would be 0.007335 pounds (or 51.3 grains) of force acting to accelerate the bullet away from the line of sight.

Imagine now if the bullet in Figure 5.6 were to have a tiny rocket motor, and were able to generate thrust equal to the force of drag. The bullet would still weather vane into the oncoming airflow. If the thrust equaled the drag, the bullet would maintain speed because the opposing forces are balanced. Furthermore, if the thrust equaled the drag, the bullet would have no net force acting across the line of sight, and there would be no wind deflection. Another way to come to the same conclusion is by looking at it in terms of lag time. If velocity is maintained, then the vacuum time of flight and the actual time of flight are the same, and the lag time is zero. As predicted by the wind deflection equation, if lag time is zero, there can't be any wind deflection.

If excessive thrust were applied, meaning more thrust than drag, the bullet would still weathervane into the wind, but now the net force across the line of sight is upwind, and the wind *deflection* would actually be upwind instead of downwind. This is exactly what happens when a rocket is fired into a crosswind, at least during the powered portion of the flight. After the solid rocket motor burns out and the thrust vanishes, the rocket drifts back downwind like a bullet.

All this *crazy talk* about bullets with thrust is not as far removed as you might think. The incendiary material in the base of tracer rounds that burns red actually produces a small amount of thrust, but it's less than the total drag of the bullet. The result is that the tracer rounds have less wind deflection (and less drop) than the other rounds. Given the intended purpose of the tracer rounds to mark the trajectory of the other rounds, and the fact that they're sometimes fired into high crosswinds (like the waist-gunner of a WW-II bomber), it's important that the tracers fly like the rest of the rounds. Furthermore, the tracer rounds lose weight in flight, unlike the normal rounds that they're supposed to be marking. This introduces a challenging design problem for the ammunition, but I won't go any further into that. We've already strayed pretty far off the topic of long range precision shooting.

Wind Gradient

Wind gradient refers to the tendency for air currents to move more swiftly farther off the ground. Even on a windy day, when you get right down in the dirt and weeds, there is essentially no wind. However, just 1 foot above the grass and weeds, the wind speed can be much higher. Likewise, if you were to sample the wind 10 feet above the ground, you would find an even higher wind speed, etc. Depending on the terrain, the wind may reach full speed at a high or low altitude. In general, the smoother the ground is (think frozen lake or flat desert), the less altitude is required for the wind to develop its full velocity. On the contrary, if the ground is covered with thick weeds, grass, shrubs, trees, etc., the wind may not reach full speed until a much higher altitude.

Figure 5.7 shows an example of a generic wind gradient. This image has no dimensions because it's intended only to illustrate the lower wind speed at lower altitude and higher wind speed at higher altitude.

Wind gradient is yet another variable associated with wind that is very difficult to account for. Shooters can only sample wind speed from their location, and only as high as their arm can hold up a wind meter. As the bullet arcs along its trajectory toward a distant target, it will rise 10, 15, even 20 feet above the ground and sometimes much more than that if the shot goes over a valley. In that case, the bullet can be flying thru a wind speed that's far greater than the shooter is able to sample from his position, or observe on the ground near the targets' location.

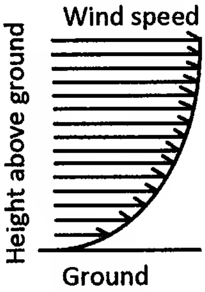


Figure 5.7. Wind Gradient

It's difficult to learn how to judge the wind speed high above the ground because you can't get sensors up there to check. However, if you know about wind gradient, you can simply add a few mph to your estimate of wind speed based on your location on the ground.

To illustrate the effects of wind gradient, Figure 5.8 compares two trajectories. Both are identical initial conditions; .308 Winchester, 175 grain bullet, 2800 fps MV.

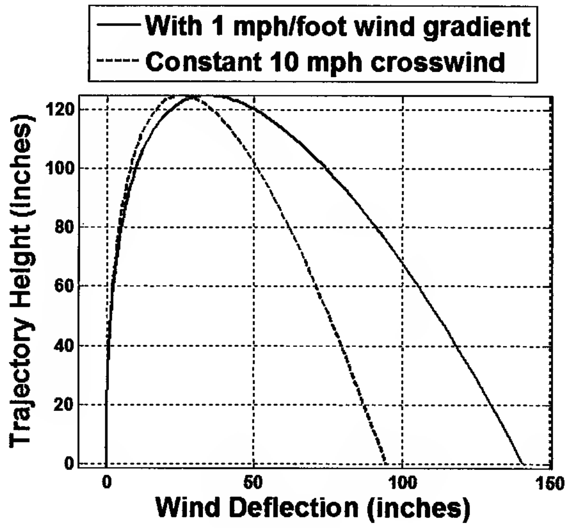


Figure 5.8. Wind Gradient effects on trajectory.

Both trajectories are from the shooters point of view, watching the bullet fly downrange, zeroed for 1000 yards. You can see that the trajectories reach a height of just over 10 feet. The trajectory marked with the dotted line represents the deflection caused by a 10 mph *constant crosswind.* The solid line shows the trajectory of a bullet fired into a crosswind that's equal to 10 mph on the ground, but increases in speed at 1 mph per foot above the ground. For this trajectory, the bullet is flying thru a realistic *wind gradient* which peaks at just over 20 mph crosswind at apogee (top of the trajectory).

It's easy to see how a shooter could be confused by the excessive wind deflection. Even if you measure the wind speed at your location, and even many locations on the ground between shooter and target, you can suffer from 1/3 more wind deflection than calculated due to the effects of wind gradient.

Calculating the Effects of a Variable Crosswind

Most ballistics programs can only calculate the deflection for constant crosswinds. As we know, such a textbook case of constant wind never really occurs in the real world due to terrain, wind gradient, and the general fluid nature of wind. In order to calculate the effects of multiple winds, the following approach is presented which closely follows McCoy **[REF 1]**. McCoy's work fully develops the crosswind weighting factor from scratch for those interested in the derivation.

The effect of multiple, or variable crosswind is calculated with the use of *crosswind weighting factors*, which will be denoted by f_{WZi}. A crosswind weighting factor is simply a number assigned to a segment of the trajectory which quantifies that segments sensitivity to wind deflection. The crosswind weighting factor is determined by range and time. The formula is long, but is actually quite simple to apply once you're familiar with the terms. It's best exercised in a spreadsheet as opposed to long-hand.

The formula for a crosswind weighting factor is:

$$f_{WZi} = [t(R) - t(X_i) - (R - X_i)/V_{Xi}] - [t(R) - t(X_{i+1}) - (R - X_{i+1})/V_{X(i+1)}]$$

Where:

fw_{Zi} is the crosswind weighting factor

R is the target range *in feet*

$t(R)$ is the time of flight at the targets range

$t(X_i)$ is the time of flight to the beginning of a range increment

$t(X_{i+1})$ is the time of flight to the end of a range increment

V_{Xi} is the velocity at the beginning of a range increment

$V_{X(i+1)}$ is the velocity at the end of a range increment

Range (feet)	Velocity (fps)	t(R) seconds
0	2800	0.000
300	2614	0.111
600	2436	0.230
900	2264	0.358
1200	2100	0.495
1500	1943	0.644
1800	1791	0.804

Table 5.1. Velocity and TOF.

The use of the crosswind weighting factor is best illustrated with an example.

Consider a .308 caliber 175 grain bullet fired at 2800 fps muzzle velocity with a G7 BC of 0.250 lb/in^2, in standard atmospheric conditions. Table 5.1 shows the range (in feet) and flight time in seconds for every 100 yards.

For the purposes of this example, we'll consider a scenario in which a 10 mph crosswind applies for the first 100 yards (300 feet) of the bullets' path. Applying the crosswind weighting factor formula, we obtain:

$$fw_{Zi} = [0.804 - 0.000 - (1800 - 0)/2800] - [0.804 - 0.111 - (1800 - 300)/2614]$$

$$fw_{Zi} = 0.042$$

To calculate the deflection of this 10 mph wind that only applies for the first 100 yards of the trajectory, simply multiply the crosswind speed in fps[6] by the crosswind weighting factor. The result will be the wind deflection in feet.

$$\text{Deflection (feet)} = 14.67 * 0.042 = 0.616 \text{ feet at 600 yards}$$

Multiply by 12 to get the wind deflection in inches.

$$\text{Deflection (inches)} = 0.616 * 12 = 7.4 \text{ inches at 600 yards}$$

Note that if the 10 mph wind blows across the entire 600 yards, the deflection at the target would be 28.5 inches.

In the next example, we'll calculate the deflection that results from a 10 mph wind that only applies to the *last* 100 yards of the trajectory. In this case, the crosswind weighting factor is calculated as:

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[6] 10 mph is 14.67 fps.

$$fwz_i = [0.804 - 0.644 - (1800 - 1500)/1943] - [0.804 - 0.804 - (1800 - 1800)/1791]$$

$$fwz_i = 0.006$$

And the crosswind deflection from this 10 mph wind over the last 100 yards is:

$$\text{Deflection (feet)} = 14.67*0.006 = 0.088 \text{ feet}$$

$$\text{Deflection (inches)} = 0.088*12 = 1.1 \text{ inches}$$

As you can see, the effect of a 10 mph crosswind over the first 100 yards of a trajectory results in much greater deflection than the same 10 mph wind applied over the last 100 yards.

Range (feet)	**Velocity (fps)**	**t(R) seconds**	fwz_i
0	2800	0.000	----
300	2614	0.111	0.042
600	2436	0.230	0.038
900	2264	0.358	0.033
1200	2100	0.495	0.025
1500	1943	0.644	0.018
1800	1791	0.804	0.006

Table 5.2. Velocity, time, and crosswind weighting factor (fwz_i).

To further tap the information available from the crosswind weighting factor analysis, let's complete Table 5.1 by calculating fwz_i for each range. Table 5.2 shows the exact crosswind weighting factor for each range segment from 0-100 yards to 500-600 yards.

So far we've only done examples that covered one range segment. What if you wanted to calculate a deflection for a wind that spans several segments? It's easy. All you do is add the deflections for each segment. For example, if you wanted to apply the 10 mph wind for the first 300 yards, it would be calculated as follows:

$$fwz_i = 14.67*0.042 + 14.67*0.038 + 14.67*0.033 = 1.66 \text{ feet} = 19.9 \text{ inches at 600 yards}$$

The deflection over the last 300 yards is calculated the same way, using the last 3 weighting factors:

$$fwz_i = 14.67*0.025 + 14.67*0.018 + 14.67*0.006 = 0.72 \text{ feet} = 8.6 \text{ inches at 600 yards}$$

There are several things to note at this point:

A) The trajectory is much more sensitive to a crosswind in the first half of this trajectory than in the second half.

B) The highest crosswind weighting factor of 0.042 is in the first 100 yards of the trajectory which indicates that the first 100 yards are the most influential to the total wind deflection at 600 yards. However, the first 100 yards does not *always* carry the most importance as will be demonstrated shortly.

C) If you add the deflection from the first and second half, the total adds up to the deflection of a constant 10 mph crosswind which verifies the math is working right.

In addition to breaking up the crosswind over various segments, it's also easy to apply different values of crosswind to each segment. For example, if the wind speed over the first 100 yards was 5 mph (7.33 fps), and the wind speed for the second 100 yards was 10 mph (14.67 fps), the calculation would be:

Deflection = 7.33*0.042 + 14.67*0.038 = 0.87 feet = 10.4 inches at 600 yards

Remember only the crosswind component is used in this calculation, not the full wind speed. For example, if a 10 mph wind is blowing from 1 O'clock, the crosswind component of that wind speed is only 5 mph. You can also calculate the effects of winds blowing in opposite directions by defining one direction as positive (+) and the other as negative (-).

Range (feet)	Velocity (fps)	t(R) seconds	fwzi
0	2800	0.000	----
300	2614	0.111	0.111
600	2436	0.230	0.113
900	2264	0.358	0.117
1200	2100	0.495	0.118
1500	1943	0.644	0.122
1800	1791	0.804	0.124
2100	1645	0.979	0.126
2400	1505	1.170	0.127
2700	1370	1.379	0.128
3000	1242	1.609	0.124
3300	1125	1.863	0.113
3600	1050	2.140	0.067
3900	1007	2.433	0.032
4200	972	2.737	0.017
4500	940	3.051	0.005

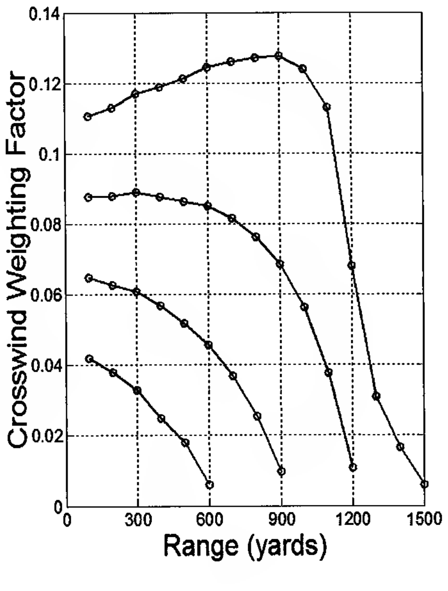

Figure 5.9. Note for the 600 yard trajectory (indicated by lower left line) the sensitivity is greatest in the first 100 yards. Likewise for the 900 yard trajectory. A 1200 yard trajectory has about the same sensitivity in the first 400 yards before dropping off. The sensitivity of the 1500 yard trajectory grows to a maximum at 900 yards before falling.

The utility in presenting this method of crosswind weighting factors is two-fold. First, it can be used by programmers to incorporate the effects of multiple winds into ballistics programs. Second, it can be used by shooters with normal ballistics programs to study the sensitivity of certain trajectories to wind. We demonstrated in the previous example, that the first 100 yards of the 600 yard trajectory had the highest crosswind weighting factor. However, that's not universally true for all trajectories and all ranges. For example, let's extend the previous example from 600 to 1500 yards and see how the crosswind weighting factors compare then.

As you can see in Figure 5.9, the crosswind weighting factor actually grows to a maximum at 900 yards, when the trajectory is 1500 yards long. In other words, the trajectory is more sensitive to wind at 900 yards than in the first 100 yards.

The 1200 yard trajectory has about equal crosswind weighting factors till about 600 yards when the value drops off.

The 900 yard factors look similar to the 600 yard factors, with the heaviest factor being in the first range segment.

Remember that the plot shown in Figure 5.9 is not a universal picture of wind sensitivity. It's highly sensitive to specific attributes of an individual trajectory. For example, if a trajectory is long enough to encounter transonic flight speeds, the crosswind weighting factors will be heavily influenced by where the bullet encounters transonic speed. The reason for this can be seen by examining the drag curve for a typical long range bullet and noting that the peak of the curve is at Mach 1.0. In other words, this is the speed that produces the highest drag coefficient, and therefore the greatest lag times (see discussion of lag time earlier in this chapter).

Notes for Programmers

For the programmer wishing to account for multiple winds, the previous presentation of crosswind weighting factors can be used to accomplish that task. Note that you're not limited to 100 yard segments, you can break the trajectory up into much smaller pieces. It then becomes possible to calculate wind deflection for any conceivable wind field (wind gradient, swirling winds, vertical eddies, etc.). The hard part here is collecting the data to describe the realistic wind field in real time.

Of course if a point mass solver is being used, the wind field can be predefined before run time, and the solver will simply use the correct wind speed at each time step thru-out the solution. The method of crosswind weighting factors is useful as a post processing step for analytic solvers that don't allow a wind field to be implemented in the solver real time.

Vertical deflection from a horizontal crosswind

There are two ways that wind can act to deflect a bullet in the *vertical* direction. One way is for the wind to actually have a vertical component, like when it blows over uneven terrain. In this way, the wind deflects the bullet the same way as a crosswind. This type of vertical wind deflection is *non-deterministic* just like horizontal wind. You have to guess about the speed and direction of the wind current and make a judgment about how much it will affect your vertical point of impact. Vertical wind currents tend to be small compared to horizontal wind, but they do exist and need to be considered especially in mountainous or rolling terrain.

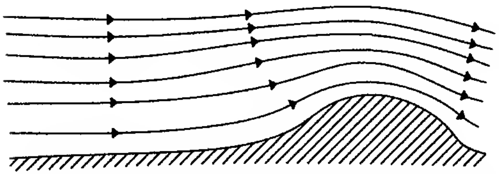
Figure 5.10. Vertical wind over terrain.

There is another way for a horizontal crosswind to deflect a bullet vertically which is less intuitive. One might ask: *How can a pure horizontal wind possibly cause a vertical deflection?* I admit it's not common sense, but I assure you it happens. The reason why has to do with the nature of spin stabilized projectiles. Remember in the previous section that discussed the mechanism of wind deflection. We said that the bullet, on emerging from the muzzle, re-aligns its axis to weathervane into the oncoming airflow. When the bullet is fired into a crosswind, this means the axis of the bullet is disturbed from its original orientation. When the axis of a spinning object is disturbed, it reacts by gyrating before converging on a new equilibrium. Since the axis of the bullet is gyrating 360 degrees, the bullet temporarily steers itself in a helix flight path. If all the steering balanced out to zero, the bullet would end up on its original path, except for the horizontal wind deflection. However, the net effect of the bullet's gyration as it finds equilibrium results in the trajectory being deflected in the vertical direction by a deterministic (predictable) amount. In other words, vertical deflection happens in a pure crosswind as a result of the pitching and yawing that takes place as the bullet finds equilibrium in a crosswind. Figure 5.11 shows the pitching and yawing motion of a 7mm 180 grain Berger VLD fired from a 1:8" twist barrel into a 10 mph crosswind blowing from left-to-right (a 9 O'clock wind) over the first 50 yards of flight. The dynamics are modeled with a 6-DOF (6 Degree Of Freedom) simulation.

To understand the plot in Figure 5.11, imagine that the bullet has a laser pointing straight out of its axis and is shining on a screen in front of it. As the bullet pitches and yaws around its center of gravity, the nose of the bullet traces out the pattern shown in the yaw vs. pitch plot.

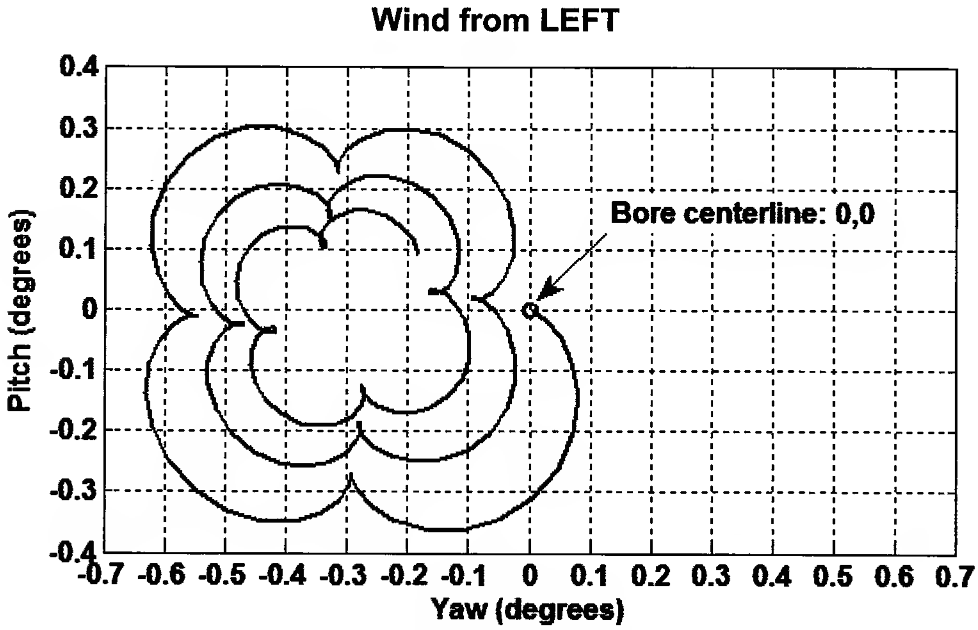

Figure 5.11. Gyrations of a bullet fired into a 9 O'clock crosswind.

First, note that the axis is generally pointing to the left of the bore line. This is consistent with the weather-vane effect shown in Figure 5.6. The bullet nose is pointed to the left of the line of sight, and the bullet will be deflected to the right (effects of the crosswind).

Next thing to notice is the magnitude of the pitch. Note that as the bullet emerges from the bore, it immediately points to the right and down. Note that the axis of the bullet pitches down more than 0.35 degrees. As the bullet nose gyrates, it's effectively steering the bullet around a small corkscrew flight path. So the bullet, on emerging from the muzzle, is steered initially *down,* because this is the direction the nose goes first. Notice that as the magnitude of the pitching-yawing motion damps and the axis points back up above the bore line, it only reaches a maximum of + 0.3 degrees (compared to the -0.35 degrees down). On every precession cycle, the axis traces farther *below* the bore line than *above* it. The cumulative effect of these precession cycles is a net deflection downward for a wind coming from the left. (This net deflection that arises from an imbalance of pitch/yaw angles is known formerly at *aerodynamic jump.* Aerodynamic jump can result from things other than wind, it can develop from bullet imbalance, and from launch dynamics which produce initial pitching/yawing conditions for the bullet.*)*

In the next plot shown in Figure 5.12, the wind was programmed to blow from the right in the 6-DOF simulation. Note that this plot shows the bullet nose pointing to the right (again, weather-vaning into the oncoming air), as well as having the nose of the bullet averaging above the bore line which will cause an upward deflection of the trajectory.

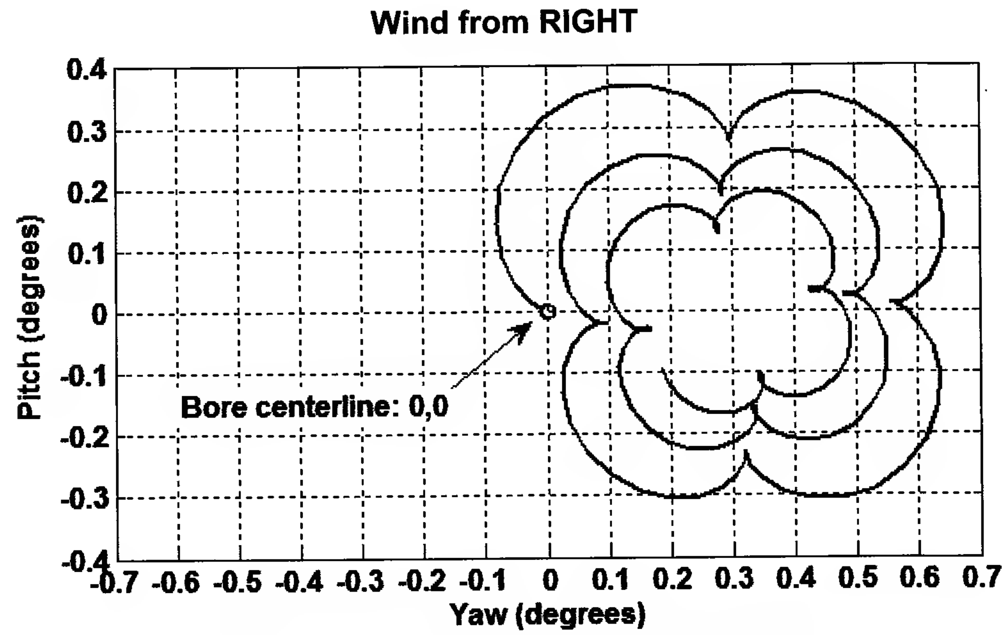

Figure 5.12. Gyrations of a bullet fired into a 3 O'clock crosswind.

To summarize what we've established so far:

- A wind from the left will deflect a bullet to the right and down.
- A wind from the right will deflect a bullet to the left and up.

Figure 5.13 simply shows the plots from Figure 5.11 and 5.12 on the same grid. Seeing the effects of the opposite wind directions together makes it clear that one results in an orientation above the bore line, and the other goes below.

Although the initial precession cycles are *lop-sided,* they will eventually converge to the zero pitch line. For this reason, the vertical deflection resulting from a crosswind is established within the first few precession cycles. As a result, we can say: for practical purposes, *the vertical deflection from a pure crosswind can be considered a constant angular value for the entire trajectory.*

It should be noted that although the pitching and yawing motion is damping with distance, similar to what some describe as a bullet *going to sleep,* the effect on the drag of the bullet is absolutely negligible. Notice the angles that the bullet achieve are less than 1/2 of one degree, and damp out quickly. This is not enough angle to induce significant drag.

The next logical question to ask is: *how much* vertical deflection can be expected from the effects described here, and how can it be predicted? The only way to directly predict the effect of the vertical deflection is to model the bullet trajectory using a 6-DOF simulation (6-Degree Of Freedom refers to the motion of the bullet in the X, Y, and Z directions, as well as its rotations on the pitch, roll, and yaw axis. Most ballistics programs only model motion in the X, Y, and Z directions, and do not model the bullet rotations). In order to simulate the 6-DOF effects directly, you would need a program capable of solving the rotations, as well as having detailed information about the bullet's mass and aerodynamic properties which are not available.

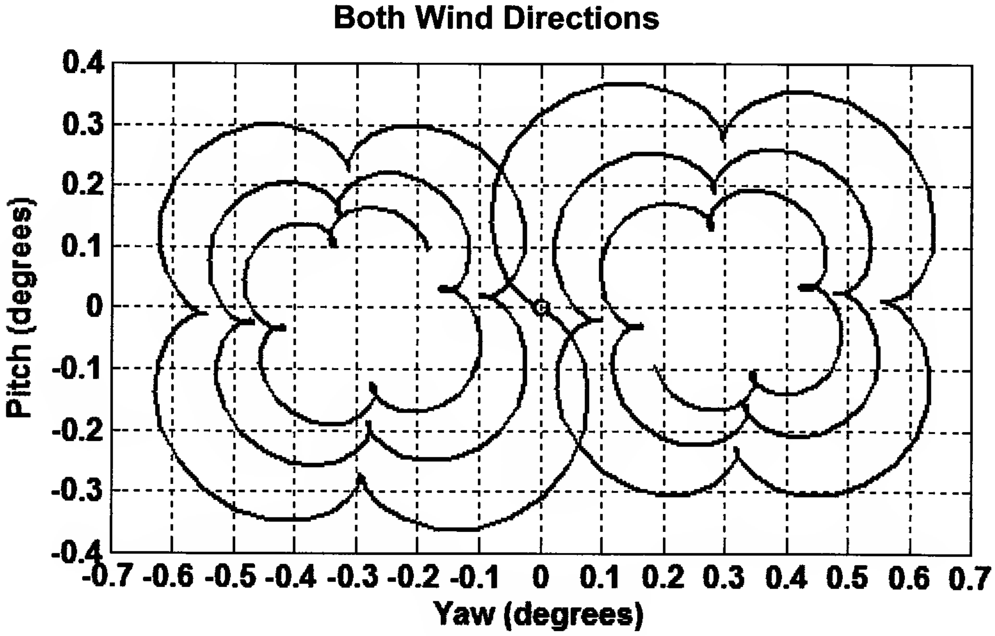

Figure 5.13. Gyrations of a bullet fired into both left and right crosswinds.

So it's not possible to directly calculate the vertical deflection, but I've developed an equation that allows for relatively easy and accurate approximations (similar to the method developed for spin drift which is presented in a later Chapter).

The equation that I've developed for the vertical deflection of a crosswind is presented here as equation 5.4.

$$Y = 0.01 \cdot SG - 0.0024 \cdot L + 0.032$$

Equation 5.4

Where:

Y is the vertical deflection in MOA of a 1 mph crosswind
SG is the Gyroscopic Stability factor (presented in Chapter 10)
L is the bullet length in calibers

As an example of how to use Equation 5.4, consider the Berger 7mm 180 grain VLD that was modeled in the previous figures. According to the Miller Stability Formula (presented in the Appendix and in Chapter 10) the SG of that bullet is 1.49 from a 1:8" twist barrel when fired at 2800 fps in standard conditions. The bullet is 1.517" long, which is 5.34 calibers in length (1.517/.284 = 5.34). Applying Equation 5.4 shows that we can expect:

$$Y = 0.01\cdot 1.49 - 0.0024\cdot 5.34 + 0.032 = 0.034\frac{MOA}{MPH}$$

That's 0.034 MOA of vertical deflection for each MPH of crosswind speed. So in a 10 MPH crosswind, we would expect a vertical deflection of 0.34 MOA according to the prediction of Equation 5.4 (up for a wind from the right, and down for a wind from the left). In fact, the 6-DOF simulation predicts a vertical deflection of 0.36 MOA for these conditions, an error of only 0.02 MOA (~0.2" at 1000 yards). This is certainly an acceptable error considering that we're estimating a complex 6-DOF effect with a simple linear equation having only two variables!

Comparisons with my 6-DOF models of other bullets at varying SG's show that Equation 5.4 is never in error by more than 0.05 MOA for the cases used in the test.

Comparing to outside sources such as the data presented in Robert McCoy's: *Modern Exterior Ballistics* **[REF 1]** also shows good agreement with Equation 5.4. McCoy calculates 0.35 MOA of vertical deflection in a 10 mph crosswind at 100 yards for the Sierra .30 caliber 168 grain MatchKing bullet[7], and Equation 5.4 estimates 0.39 MOA, an error of only 0.04 MOA.

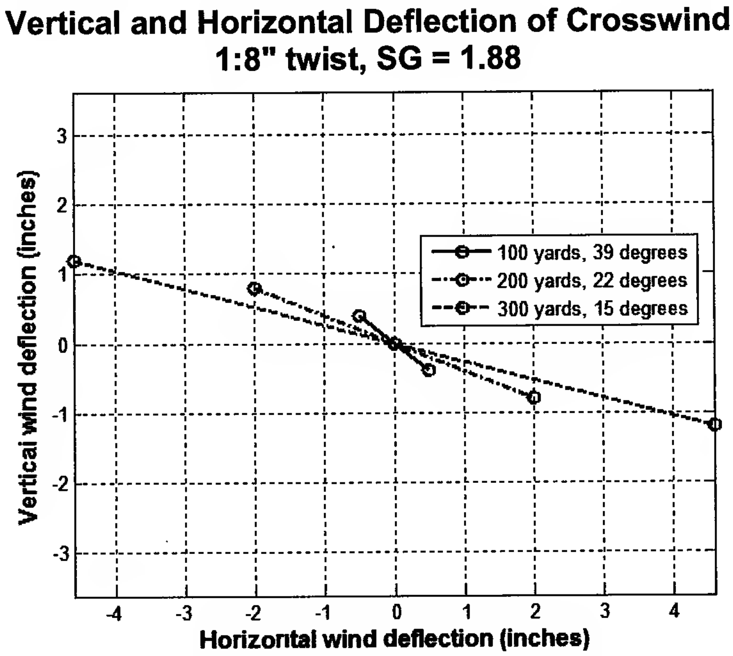

Figure 5.14. Angle of deflection shallows as range increases

The issue of vertical wind deflection is also addressed by Harold Vaughn in Chapter 10 of his excellent book: *Rifle Accuracy Facts* **[REF 2]**. Harold focuses on the angle that bullet holes will make when fired in a varying crosswind. Putting the deflection in terms of an angle can be misleading because the angle is only good for one range. The reason is because the vertical component of deflection is a fixed angular value which stays the same at all ranges, but the wind deflection is a value that grows in angular value with range. The wind is a force that continues to act to deflect the bullet along its entire trajectory, whereas the vertical deflection is established within 10-20 yards of the muzzle. Figure 5.14 shows how the vertical and horizontal deflections compare at various ranges. In other words, if you were to shoot the same rifle at 3 distances in a crosswind that varies from 10 mph left to 10 mph right, the groups would form along the lines indicated here. By the time the bullet reaches 1000 yards, it will have deflected 62.2" sideways, but still only 0.38 MOA (4") in the 10 mph crosswind. The resulting angle of deflection is less than 4 degrees.

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[7] A bullet that's 3.98 calibers in length, fired at 2600 fps from a 1:12" twist barrel, SG = 1.7.

Figure 5.15 shows the same conditions as Figure 5.14, except that the rifling twist rate is 1:9", resulting in an SG of 1.49 instead of 1.88. In this case, Equation 5.4 predicts the vertical deflection of the crosswind to be only 0.035 MOA/MPH. The resulting angle of deflection is therefore reduced. Note that the horizontal wind deflection is unaffected by the change in twist rate and SG, but the vertical deflection is. At 1000 yards, the angle of deflection is 3 degrees.

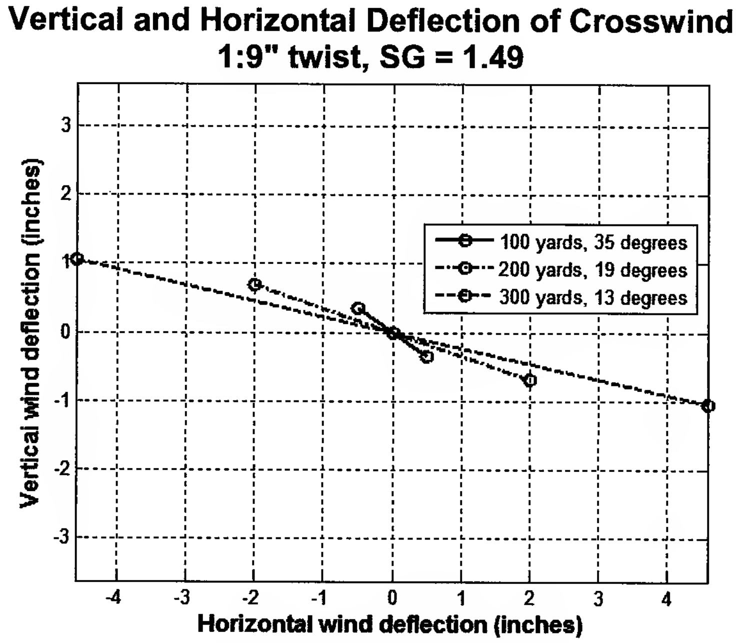

Figure 5.15. Angle of deflection is shallower for lower SG.

So far we've discussed the effect of pure crosswinds on the horizontal and vertical bullet deflection. How are these dynamics affected if the wind is blowing from another direction? What if the wind is coming from 1 O'clock or 2 O'clock? In those cases, there is a component of crosswind and a component of head or tail wind. In general, a headwind will cause a bullet to slow down faster and strike the target lower and vice versa for a tail wind. However the effect is so small as to be negligible, even at long range in most cases. For example, a 10 mph headwind will affect the vertical impact of a bullet by less than 0.01" at 100 yards, and only 1.4" at 1000 yards. For all intents and purposes, if you fired in wind conditions that rotated around the clock every 30 degrees (12 O'clock, 1 O'clock, 2 O'clock, etc.) the resulting target would look the same as those shown in Figures 5.14 and 5.15. Impacts would lie on a straight line that slants from high left to low right. In other words, the 11 O'clock wind would produce practically the same POI as a 7 O'clock wind because they both have the same crosswind component. The fact that the 11 O'clock wind has a headwind component and the 7 O'clock wind has a tail wind component is practically irrelevant. You can use the included ballistics software to calculate the effect of a head and tail wind to see for yourself how little it affects trajectory.

Note that the direction of vertical deflection depends on the direction of rifling twist. If you fired bullets from a *left twist* barrel, they would form a slant in the opposite direction as a *right twist* barrel.

Practical Application

For those who've managed to stick with the discussion this long, you're probably thinking about how to apply this knowledge of vertical wind to your shooting. In this section, I'll discuss my thoughts on what to do with this information depending on your shooting application. As we consider the various shooting disciplines, remember that the deterministic vertical deflection caused by aerodynamic jump is not the only way wind can deflect a bullet in the vertical direction. There are also vertical wind currents to consider which will depend on the terrain over which you're shooting.

Short Range Benchrest

Short range Benchrest (up to 300 yards) is probably the discipline with the most to gain from an understanding of vertical wind deflection, and I say that for several good reasons.

First of all, the terrain over which 100 and 200 yard matches are fired tends to be relatively flat, and the bullets aren't flying high over the ground as they do on longer range shooting. This means the chaotic effects of vertical wind currents are minimized, and the deterministic vertical deflection caused by aerodynamic jump is more dominant.

Secondly, as we can see from Figures 5.14 and 5.15, the angle of deflection is most severe at short range[8]. Let's say you shoot 3 shots in zero wind and they cluster into one hole, then the wind picks up from the left. If you judge the horizontal effect of the wind and hold off the perfect amount to the side, your shot will be out of the group- LOW. If you only hold left and right for the wind pick-ups and let-offs, you're not accounting for all the effects of the wind. Granted this is difficult to see in reality because you're generally trying to shoot within a small window of wind speeds, not zero to 10 mph, but the effect is still there and groups would be smaller if it were compensated for.

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[8] Although the magnitudes of deflection will be different for various types of bullets, the general trends will be the same.

Consider the practice of short range Benchrest shooters to choose the slowest possible twist rate that will stabilize their bullets for use in competition. One rationale behind choosing the slowest twist rate has to do with minimizing the effects of bullet imbalance (discussed in Chapter 10). However, there is another advantage of slower twist barrels that is less apparent, and it has to do with vertical wind deflection. Remember that slower twist rates resulting in lower SG results in a shallower angle of wind deflection. That could be a very strong reason why Benchrest shooters favor slow twist barrels. If the bullet is deflected at an angle proportional to twist rate, and shooters only use pure horizontal holds for wind deflection, those with the slowest twist rates incur the least vertical error in group sizes.

The final reason I would suggest that short range Benchrest shooters consider the effects of vertical wind deflection is because the effect is quite significant in comparison to the precision capabilities of the equipment. In other words, the effect is not *in the noise* so to speak. 1/4 MOA of vertical deflection is quite possible in a short range Benchrest contest, and can be quite detrimental to a group and aggregate.

Long Range Benchrest and F-class Competition

When you stretch the range out, it becomes less common for the terrain to remain truly level and even between the shooter and target. Every long range I've been on has some kind of vertical terrain features that will cause vertical wind currents to greater or lesser extent as the wind changes speed and direction, even if the terrain features are just firing mounds downrange.

The uncertainty introduced by these vertical wind currents makes it extremely difficult to *resolve* any vertical deflection being caused by aerodynamic jump vs simple wind deflection from vertical wind. Also, groups at long range tend to be proportionally larger at longer range (.25 MOA at 100 compared to .5 or .75 MOA at 1000). This makes it more difficult to resolve the vertical wind deflection from the inherent group dispersion. Add the uncertainties of terrain, larger group sizes, and shallower deflection angles, and the effects of vertical wind deflection from aerodynamic jump become far less important to the contest as compared to short range Benchrest.

FULLBORE, Palma Style Prone/Sling Shooting

Consider all of the reasons given in the previous section, plus the fact that groups are generally even bigger for unsupported prone shooters (1 MOA +), the effects of aerodynamic jump are even less important in these styles of shooting.

Figure 5.16. Flag showing vertical wind

There is one exception to consider with this style of shooting, and it has to do with the rate of fire. Many long range Benchrest and F-class shooters employ the strategy of firing quickly, to get all their shots off in a relatively short time span, thereby minimizing the condition changes they have to endure. This can be an effective strategy that 'sling' shooters cannot benefit from because the rate of fire can only be so fast from the less stable position. As a result, the sling shooters often find themselves shooting thru a wider range of wind conditions in a given string, which means they would incur more vertical error from their windage corrections.

Finally, vertical deflection from crosswind will show up as an elevation 'bias' when shooting in a strong crosswind with regards to elevation [sight] zeroes. For example, if you shoot 1000 yards one day and come off the line with a sight setting of 34.5 MOA elevation, then shoot the next day on the same range, same temperature, and only use 34.0 MOA, it might be confusing. However if the first day was zero wind, and the second day you had a 10 MPH wind from the right, it would explain why your elevation zero appeared to shift. Wind from the right pushes your bullet to the left *and up,* which means you would need less elevation to zero in that wind condition.

Remember that even though the aerodynamic jump effect is always there, many times the terrain will mask its affects with more major effects of actual vertical wind currents.

Long Range Hunting and Tactical Shooting

This discipline of shooting is a mixed bag that can present all kinds of unique challenges. In general, I suspect that the overwhelming amount of variables involved in most field shooting will mask the subtle effects of aerodynamic jump. For example, if you're shooting uphill/downhill, or across a canyon and there's any wind present at all, chances are there will be a significant component of that wind blowing up thru or down thru your line of sight and that will be the dominant affect of the vertical wind.

However, another unique feature of this kind of shooting is that it tends to be done without *sighters.* In other words, first shot hits are far more important than in the various traditional styles of competition shooting. This means that shooters are compelled to calculate and correct for the effects of all known deterministic effects in order to maximize the chances of a first shot hit. For this reason, I would advise calculating (or using a program that calculates) vertical wind deflection when doing this kind of shooting. It can only get you closer to your point of aim. In a situation where a first shot hit is required, it simply doesn't make sense not to account for as many known variables as possible provided there's time. You will still have to dope the effects of vertical wind components, but at least the know-able part of the problem is being handled right which reduces the total error in the solution.

Practical take-aways from the wind chapter

Much of the material in this chapter was technical. I'll provide a short summary of the important points.

- Wind deflection is the most influential non-deterministic element in long range exterior ballistics.
- The best strategy for beating the uncertainty of wind deflection is to *minimize its uncertainty and its effects.*
- Lag time is the fundamental measure of merit for wind deflection. Lag time is reduced by using high BC bullets and high muzzle velocity.
- In a trade-off between low BC (light weight) bullets at high speed compared to high BC (heavy) bullets at reduced speed, the high BC bullets at lower speed will produce less lag time and less wind deflection.
- The academic debate between *near wind vs far wind* is trumped by the unique realities of wind patterns specific to each range. The best policy for shooting in the wind is *flexibility* and critical assessment of the features unique to each range.
- Wind does not *blow on the side* of a bullet to cause deflection. Instead, the bullet *weathervanes* into the oncoming airflow. A crosswind will make the bullet fly at a small angle to the line of sight. The aerodynamic drag applied to the bullet acts directly back along the bullets axis, which effectively *pulls it away* from the line of sight.
- Wind gradient is when the wind velocity increases with increased height above the ground. It can be difficult to judge the wind speed high above the ground when shooting over valleys where there are no indicators, but you can usually count on higher velocity winds in such cases.
- Crosswind weighting factors can be used to calculate the effects of multiple winds. The most wind sensitive portion of a bullet's trajectory is not always the first segment. If the bullet will go transonic during its flight, that will dictate where the bullet is most sensitive.
- Aerodynamic jump is a mechanism by which a bullet can have a vertical deflection when fired into a purely horizontal crosswind. This deflection is a constant angular deflection, roughly equal to 0.03 to 0.04 MOA per MPH of crosswind speed, and it depends on the gyroscopic stability of the bullet at the muzzle. The deflection is down for a left-to-right crosswind, and up for a right-to-left crosswind. These directions are reversed for a left twist barrel (very rare).

Chapter 6: Gyroscopic Drift

Gyroscopic drift, or *spin drift* as it's commonly referred to as, is an issue for long range shooting, and something worth considering. Spin drift occurs only in the horizontal plane, and generally has less of an effect than wind deflection. Since spin drift is a deterministic variable, it is more predictable than wind deflection. For example, wind deflection might be between 5 and 10 feet for two consecutive long range shots, but spin drift will always be the same for a given bullet/velocity/spin rate at that range. We're getting ahead of ourselves. First, what is spin drift, and why does it happen?

A Brief Explanation of Spin Drift

Spin drift is a unique consequence of spin stability. Spin stability works because the spin axis of the bullet is rigid, and that rigidity is stronger than the aerodynamic overturning torque that's applied to the bullet's nose. The fact that the bullet axis maintains rigidity is *mostly* a good thing, but on long range trajectories, it causes a little bit of a problem. Imagine a bullet launched at a small initial upward angle towards a distant target. If the axis of the bullet remained absolutely rigid, it would not be able to *trace*, or *weather-vane* along the trajectory, and would impact the target in the same nose high orientation that it was launched at. Part of the fundamental definition of stability (fin or spin stability). is that the projectile stays pointed into the oncoming air flow. That's why if you shoot an arrow at a high angle, the arrow weather-vanes along its trajectory and sticks in the ground point first. Bullets that are spin stabilized will do the same thing, *but the rigidity of the bullets spin axis resists the tendency of the projectile to naturally weather-vane with the trajectory.* This resistance of the spin axis to *bend* with the trajectory is what starts the process that results in spin drift.

The exact interaction between the inertial and aerodynamic effects that result in the epicyclic motion of spin stabilized projectiles is outside the scope of this book. Suffice it to say that when the spin axis of the bullet is *forced* to weather-vane (trace) with the trajectory, it reacts by pointing its nose slightly to the right for right twist barrels, and to the left for left twist barrels[9]. The spin stabilized bullet is tracing with the trajectory because it's stable, but unlike a fin stabilized projectile, it reacts with this slight out of plane angle which is known as the *yaw of repose.* The fact that the yaw of repose points to the right for right twist barrels causes the bullet to *steer* itself in that direction. Keep in mind that the yaw of repose for long range trajectories is typically less than 0.1 degrees, so the steering effect isn't very strong at any particular point. However, the steering effect is *persistent* and builds to significant levels over long range trajectories.

Dealing with Spin Drift

The previous section is a basic description of the interactions that cause spin drift. Now that we understand basically how and why spin drift happens, I'll describe how to quantify it so you can correct for it.

Since spin drift is such a subtle effect compared to wind deflection, it would be extremely difficult to measure it experimentally. You would need absolutely calm conditions, an extremely precise rifle, perfectly leveled and repeatable sights in order to measure it with any kind of certainty. For these practical reasons, it's very difficult to measure spin drift directly. Furthermore, most commercial ballistics programs lack the capability to calculate spin drift. Those that do calculate spin drift are quite expensive, and require inputs that can be very tedious to generate. The ballistic program included with this book has the capability to calculate spin drift using the equation presented below.

Development of the spin drift equation

A 6 Degree Of Freedom (6 DOF) computer program, combined with aerodynamic prediction software, is capable of modeling all of the dynamics that cause spin drift and other complex effects. The 6 DOF program is too complicated for general use, but it is possible to run the program for a set of representative bullets and study the level of spin drift for each. It's then possible to key in on the most important variables related to the spin drift and produce a predictive equation that can be used to characterize the effects of spin drift rather than calculate it directly. This is a common approach in engineering for capturing the effects of complex phenomena that are impossible or too difficult to measure directly. This approach was used to develop the spin drift equation presented in this chapter, and that's used in the included software for calculating spin drift. Several sources of spin drift data were used including some data published for the Sierra 168 grain international bullet in Robert McCoy's book: *"Modern Exterior Ballistics"*, and some radar range data for the .510 caliber 750 grain Amax bullet out to 2500 yards.

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[9] Left twist barrels are very uncommon, which is why spin drift is always thought of as being to the right.

My analysis of these high fidelity sources of spin drift has revealed that a small number of easily obtained variables can be used to estimate spin drift. The key parameters are: gyroscopic stability factor (SG), and the time of flight. When you think about it, these parameters actually contain a lot of information. For example, the gyroscopic stability factor contains information about the bullets mass/inertial properties as well as the aerodynamic overturning moment which plays a big role in the process of spin drift. Also, the bullet's time of flight reflects information that's determined by its muzzle velocity, BC, and distance flown. The following equation is my best effort to match the available spin drift data using SG and time of flight.

$$Drift = 1.25(SG + 1.2)tof^{1.83}$$

Equation 6.1

Where:

Drift is spin drift in inches (in the direction of rifling twist)

SG is the gyroscopic stability factor as predicted by the Miller twist rule.

tof is the bullets time of flight

Verifying the spin drift formula with live fire

The high fidelity test data and 6-DOF modeling data that were used to develop the spin drift equation are presented at the end of the chapter. I relied mostly on 6-DOF modeling to create the necessary body of information.

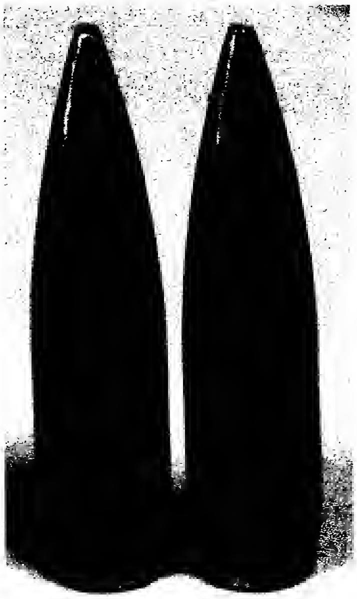


Figure 6.1. Berger 175 OTM Tactical bullets fired and recovered from 1:10" right and left twist barrels.

With the formula established, some limited live fire testing was done to compare.

The challenge of measuring spin drift is obvious given the effect of the ever-present wind. Even if you wait for the elusive *no wind* day and shoot long range to measure spin drift, you'll never know if your horizontal bullet deflection is truly absent of any wind effects. There is a clever way around this problem.

Historically, *drift firing* is known as the practice of simultaneously firing two rifles which have barrels rifled in the opposite direction; one right, one left **[REF 1]**. The rifles are zeroed to hit the same point of impact at 100 yards. Then, with sights plumb, both rifles are fired at long range targets. In the event there is wind blowing, it will deflect the bullets from both rifles equally because they're being fired simultaneously in the same condition. The resulting lateral separation of the two groups is *two times* the actual spin drift of each group. Using this method, actual spin drift can be experimentally measured with reasonable certainty. We can then compare the spin drift formula to see how accurate it is.

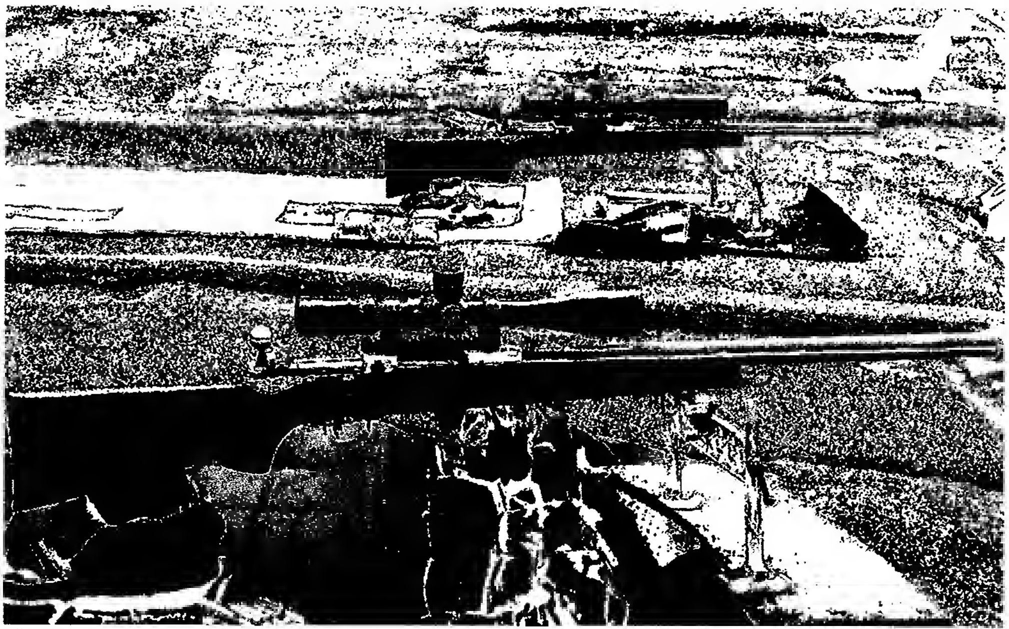
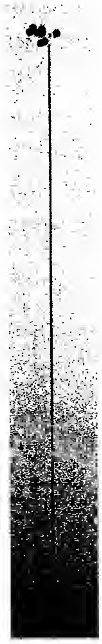


Figure 6.2. Simultaneous firing of two identical rifles set up with opposite twist barrels. Group separation at long range allows direct measurement of spin drift.

Figure 6.2 above shows the two rifles used to conduct the drift firing experiment. Both are Savage Precision Target actions with 24" Bartlein barrels, 5.5-22X Nightforce NXS scopes mounted on 20 MOA rail, HS Precision stocks modified for use with F-Class TR style bi-pods. The bi-pods are important to this particular experiment due to their resistance to tilt (cant).

Both barrels are 1:10" twist, however the far rifle in Figure 6.2 has a left twist, while the closer rifle has a right twist barrel. Both rifles were zeroed to the same point of impact at 100 yards, directly above the line of sight, at the elevation required to zero at 1000 yards. The rifles were zeroed high on a plumb line at 100 yards in order to eliminate the variable of scope tracking. You can see the 100 yard target to the right, where both rifles volley fired 5 shots into the same group. Total group size is 1.1" with that flier on the right. Without that flier, the group size is 0.75". Remember, this is a 10 shot group comprised of firing 5 shots from each of *two different rifles*. Typical groups for each rifle are around 0.5" at 100 yards. The combined 10 shot group of 0.75"-1.1" suggests that the two rifles are zeroed within about 0.25" at 100 yards (about ¼ MOA). Remember for this test we're mostly concerned about the horizontal group centers.

After the point of impact was established and matched for both rifles, they were both turned to the same 1000 yard target where 10 shots each were fired at the same point of aim. Note there was a mild prevailing wind which required both rifles to dial on 1.5 MOA right from the 100 yard groups. With the same sight settings on both rifles, the groups in Figure 6.3 were fired. The shots were fired within a few seconds of each other to minimize environmental influences.



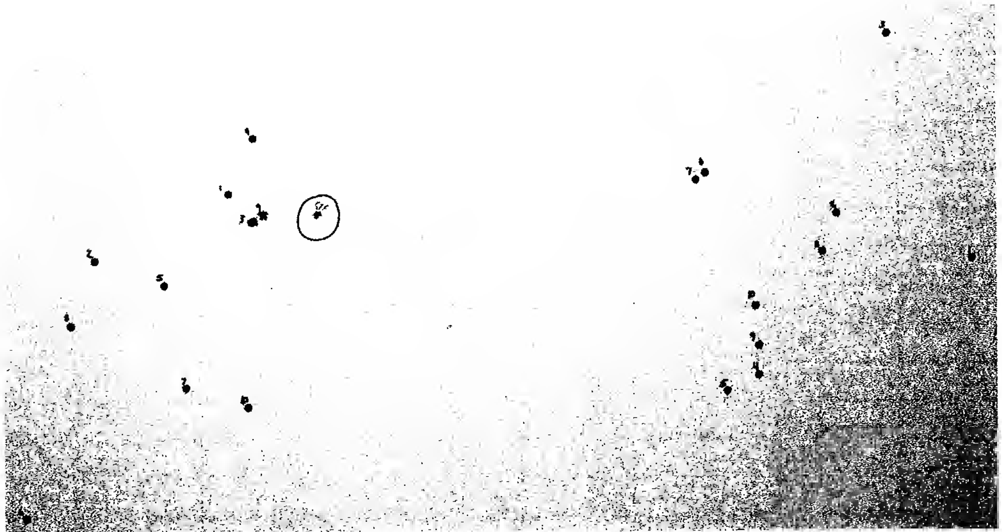
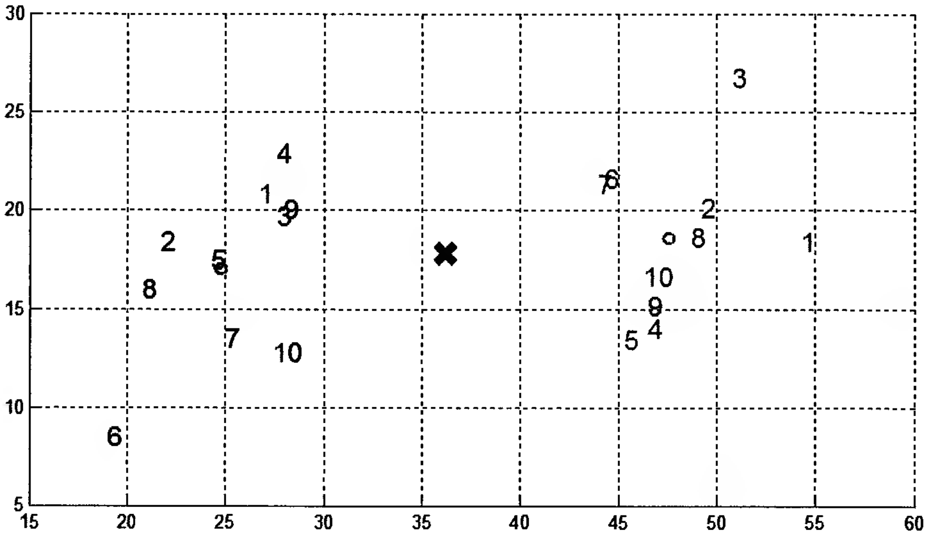


Figure 6.3. Berger 175 OTM's fired from 1:10" Left vs. 1:10" Right twist barrels. Group centers separated by 22.8", indicating each group drifted 11.4" from zero.

The circled hole in Figure 6.3 is where the aiming disk was placed in the target (6" black shot spotter). The wind was very steady for all 10 shots, and as a result you can see the groups are distinctly separated. Each shot was plotted and numbered by an observer in the target pits so we know what order the shots are in.

Figure 6.4 is a virtual mapping of the group based on measuring the X and Y locations of each shot. The coordinates and lateral (X) separation are tabulated for each shot. The average separation between shots (which is also the separation between group centers) is 22.8”. That means that each barrel produced 11.4” of spin drift *from center.*



Shot#	Left Twist		Right Twist		Lateral separation
	X	Y	X	Y	
1	26.7	20.8	54.3	18.4	27.6
2	21.7	18.4	49.2	20.1	27.5
3	27.6	19.7	50.8	26.7	23.2
4	27.6	22.9	46.5	14.0	18.9
5	24.3	17.5	45.3	13.4	21.0
6	19.0	8.5	44.3	21.6	25.3
7	25.0	13.5	44.0	21.3	19.0
8	20.8	16.0	48.7	18.6	27.9
9	28.0	20.0	46.5	15.1	18.5
10	27.4	12.8	46.3	16.6	18.9
				Average:	**22.8”**
				Standard Error:	**1.3”**

Figure 6.4. Coordinates of each shot fired from left and right twist barrels. Group centers were 22.8” apart laterally, indicating a measured spin drift of 11.4”.

The standard error of 1.3” is also for the lateral separation, which is twice the spin drift. In other words, the standard error for the measurement of spin drift *from zero* is ½ of 1.3”, or 0.65”. Remembering the meaning of standard error, we can say with 95% confidence that ***the measured spin drift was between 10.1" and 12.7", which is 11.4"** +/- **2 standard errors of 0.65".***

If you consider that the 100 yard zero might not have been *perfectly* aligned for both rifles, we might allow for slightly more error in the above numbers.

So how does this measurement compare with the calculation for spin drift? Based on a: 1:10" twist, 175 grain .308 caliber bullet that's 1.268" long, fired at a muzzle velocity of 2660 fps with an air temperature of 37 degrees F, station pressure of 28.95 inHg, and relative humidity of 70%, the stability factor (SG) of this bullet is estimated as 2.24 using the Miller Twist Rule. Also, based on these conditions and a G7 BC of .258, the time of flight is calculated as 1.687 seconds. With all of this information, we can apply the formula for estimating spin drift (Equation 6.1):

$$Calculated\ Drift = 1.25(SG + 1.2)tof^{1.83}$$

$$Calculated\ Drift = 1.25(2.24 + 1.2)1.687^{1.83}$$

$$Calculated\ Drift = 11.2\ inches$$

There's one small correction we need to make to this result, and that's accounting for the spin drift at 100 yards. Remember that both rifles were zeroed to hit the same point of impact at 100 yards, which means at that range, their spin drift was zeroed out. With a 100 yard time of flight of 0.1167 seconds, we can apply the above formula to arrive at 0.08" of spin drift at 100 yards. Subtracting this angular correction from the calculation above results in ***10.4" of spin drift between 100 and 1000 yards; calculated.***

This calculation falls within the measured 10.1" to 12.7" experimental result which means that in this case, the approximate calculation provided a result which was within measurement uncertainty.

This example showed the approximate spin drift formula to be quite accurate for this particular bullet. Before leaving the subject, let's see how accurately the formula predicts spin drift for another bullet.

We'll next consider the Berger .30 caliber 185 grain Long Range Boat Tail (Juggernaut). With everything else the same, the test barrels will produce a lower stability level (SG) for this bullet compared to the 175 OTM's. The picture on the following page shows the tall target used to confirm 100 yard point of impact for both rifles with this bullet.

This group was volley fired the same as the group of 175 grain bullets, and measures just under 0.9" for the 10 shots (5 from each rifle).

When we turned the rifles downrange, the wind had calmed way down and only ½ MOA right was needed to center the groups on the 1000 yard target. With both rifles dialed to the same elevation at 100 yards and ½ MOA right windage, the groups in Figure 6.5 were fired in similar fashion as was done with the 175's. As expected, you can see there is less distinct group separation for the longer 185 grain bullets. The greater length of the bullets results in a lower stability factor when fired from the 1:10" twist barrels, and so spin drift is less compared to the shorter 175's which had a higher SG.

The circled hole in the center was where the aiming point was stuck, and the line separates the left twist from the right twist groups. Although the wind stayed mostly steady for this test, it did pick up for one shot, which blew equally out of both groups. The digitized target in Figure 6.5 shows that shot #6 is about 10" to the right of each group center.

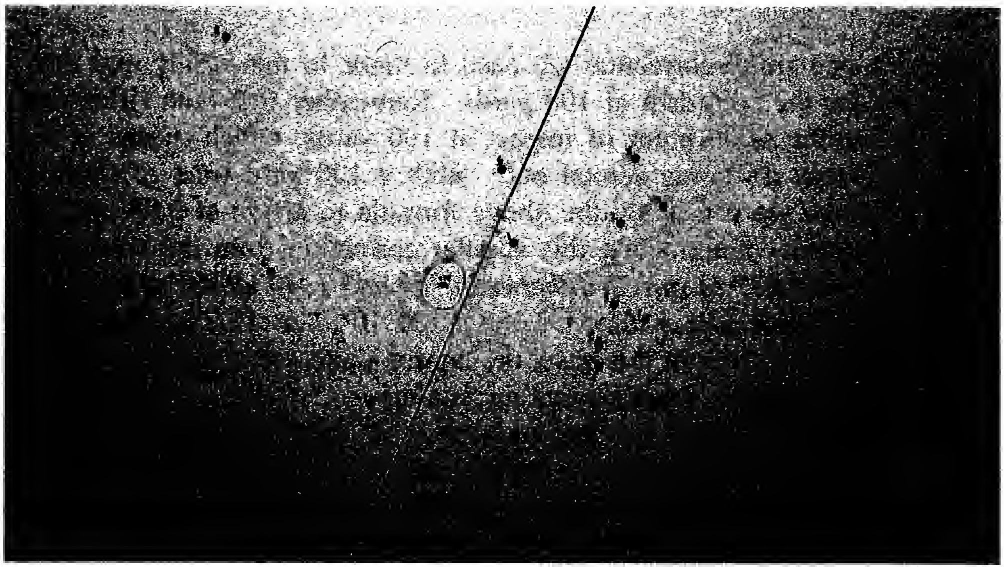
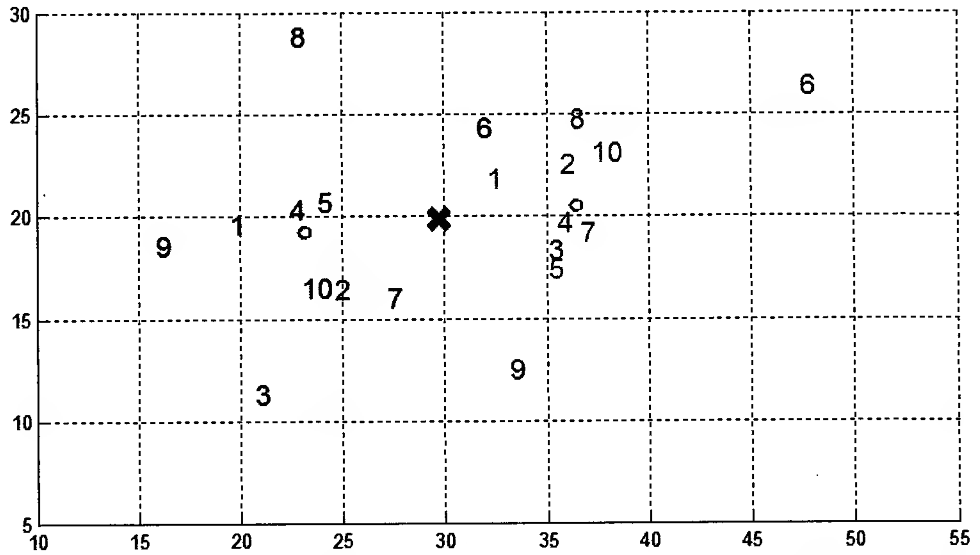


Figure 6.5. Berger 185 Long Range Boat Tails fired from 1:10" Left vs. 1:10" Right twist barrels. Group centers are separated by 13.3", indicating each group drifted 6.7" from zero.



Shot#	Left Twist		Right Twist		Lateral separation
	X	Y	X	Y	
1	19.5	19.6	32.1	21.8	12.6
2	24.6	16.4	35.7	22.5	11.1
3	20.7	11.3	35.1	18.3	14.4
4	22.4	20.3	35.5	19.7	13.1
5	23.8	20.7	35.1	17.4	11.3
6	31.6	24.3	47.4	26.4	15.8
7	27.2	16.0	36.7	19.2	9.5
8	22.5	28.8	36.2	24.7	13.7
9	15.9	18.5	33.2	12.5	17.3
10	23.0	16.5	37.2	23.1	14.2
				Average:	**13.3”**
				Standard Error:	**0.73”**

Figure 6.6. Coordinates of each shot fired from left and right twist barrels. Group centers were 13.3” apart laterally, indicating a measured spin drift of 6.7” from center.

In the case of these 185 grain bullets, the group separation was only 13.3”, which means that the spin drift from center is only 6.7” on average. The standard error indicates a 95% confidence interval of 6.0” to 7.4” for the measurement uncertainty.

Based on the Miller stability formula, this bullet has a gyroscopic stability factor of 1.91 from a 1:10” twist in the conditions it was fired. With an average muzzle velocity of 2630 fps, and a G7 BC of .283, the time of flight is predicted as 1.640 seconds. Applying the spin drift formula results in an estimated total spin drift of 9.6” at 1000 yards. Subtracting out the 0.08” from aligning point of impact at 100 yards (0.8” at 1000 yards), and the corrected 1000 yard spin drift calculation is 8.8” for the 185 grain bullet, which is 2.1" more than measured. In other words, the formula over-estimated spin drift by 2.1" at 1000 yards.

So the spin drift formula had a little more error for the 185 grain bullet than it did for the 175 grain bullet. The important take-away from this limited live fire verification is that the spin drift formula does a pretty good job of predicting actual spin drift, despite the fact that it's accounting for highly complex dynamics with relatively simple calculation.

The following sections present the details of the data that the spin drift formula is based on.

Sierra .30 caliber 155 MatchKing

The first bullet that high fidelity data was generated for is the .30 caliber Sierra 155 grain Palma bullet[10] at 3000 fps muzzle velocity. This bullet is representative of the class of bullets used in long range and Fullbore international target shooting. The 6 DOF program was used to generate spin drift data for two different barrel twists (1:13" and 1:11" twist) that naturally result in two different gyroscopic stability factors (1.72 and 2.40) as predicted by the Miller stability formula presented in Chapter 10. For this bullet, the simple *estimate* generated by Equation 6.1 results in a slight under prediction of the spin drift at all ranges as compared to the 6 DOF prediction. The error is minor though. At 1000 yards as this bullet is nearing the transonic region, there is less than 1" of error in spin drift. The spin drift for this bullet in the 1:13" twist barrel is 1.76" less than the 1:11" twist barrel at 1000 yards as predicted by 6 DOF simulation. Equation 6.1 predicts 2.06" difference between the two barrel twists.

It's important to keep these errors in perspective. The 6 DOF calculation is not *truth* data, it's just a higher fidelity prediction of something that's very hard to predict. If you were to actually measure the real spin drift of this bullet, you would find it doesn't exactly match either the 6 DOF prediction or the estimate of Equation 6.1. But I would bet on the 6 DOF prediction to be closer. Since it's not possible to generate 6 DOF spin drift data for all bullets, we can use Equation 6.1 as a reasonable estimate to give us an idea of the effect so we can do our best to correct for it. *If the actual spin drift is 8" at 1000 yards, it's better to make a slightly inaccurate correction of 6" or 10" than it is to make no correction at all, even if there is 4 feet of wind deflection!*

Sierra .30 caliber 168 MatchKing

The next bullet considered in the development of Equation 6.1 is the Sierra 168 grain International bullet. The *high fidelity* data for this bullet was also generated by a 6 DOF simulation, but this one was run by Robert McCoy, and the data for the bullet was generated by very accurate spark range measurements. This bullet produces the poorest match with the estimate of Equation 6.1, yet it's still within 3.14" error at 1000 yards for the 1:10" twist barrel. This bullet is an oddball, especially at long range due to a unique dynamic instability that causes it to fly at increasingly high levels of average yaw. Since this bullet is somewhat of an oddball, it's less concerning to me that Equation 6.1 produces such a poor match for it.

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[10] I'm referring here to the original Sierra Palma bullet, #2155. This clarification is necessary because of the new Sierra Palma bullet that was made available in 2009.

Sierra .30 caliber 175 MatchKing

The next bullet is another Sierra, the .30 caliber 175 grain MatchKing used extensively in military and law enforcement sniper ammunition at extended ranges. In this example, the data is run out to 1300 and 1500 yards to see how well the estimate of Equation 6.1 holds up thru and below transonic flight speeds. As you can see in the plots at the end of this chapter, up to 1000 yards, there is less than 1" of error for both barrel twists. The max error is at 1500 yards from the 1:12" twist barrel, where the 6 DOF predicts 30.84" of spin drift, and Equation 6.1 predicts 28.38", an error of 2.46". At 1300 yards, the bullet is traveling around 1000 fps; below the speed of sound, but still in the transonic region. At 1500 yards, the bullet is well below transonic speeds, traveling around 950 fps. You can see that as range increases beyond 1000 yards and the bullet goes subsonic, the spin drift estimated by Equation 6.1 maintains a good match to the higher fidelity 6 DOF results.

Berger 7mm 180 VLD

The next bullet considered in the spin drift study is the 7mm 180 grain Berger VLD at 2800 fps muzzle velocity from 1:9" and 1:7" twist barrels. This bullet is an outlier because of its long secant ogive and extremely high BC. Since it's an outlier, it can be expected to exhibit more error than the other more nominal bullets used to train Equation 6.1. As it turns out, this bullet does generate the most error between the 6 DOF model and Equation 6.1, but it's still only 8" of error out of 21.04" of drift at 1500 yards. Keep in mind that one ¼ MOA click will move a scopes crosshairs by just under 4" at 1500 yards. To put this *error* in perspective, if you corrected for spin drift based on Equation 6.1, the correct number of ¼ MOA clicks would be 6, which moves the crosshairs 23.6" (closest you can get to 21.04" with ¼ MOA clicks). So in this *max error* case, you can say that Equation 6.1 has *less than 1 click of error at 1500 yards*. Assuming the 6 DOF prediction of 21.04" is completely accurate, your 6 clicks only puts you 2.6" off.

I'm only going thru all this to demonstrate that even in the worst case scenario, Equation 6.1 is accurate to within practical limits, even to extended ranges and transonic/subsonic speed.

Sierra 6mm 80 grain Blitz

I wanted to include a bullet in the study that's not typically used in very long range shooting. I chose a typical .243 caliber varmint bullet of 80 grains, the Sierra 80 grain Blitz at 3500 fps.

This bullet goes transonic around 800 yards. Assuming it doesn't tumble at transonic speed from a lack of dynamic stability and actually makes it to 1000 yards, Equation 6.1 is only about 1.8" in error compared to the 6-DOF prediction. This shows that Equation 6.1 maintains acceptable accuracy for smaller caliber, lighter weight bullets as well as the heavy large caliber bullets typically used for long range applications. A bullet like this is likely to suffer such exaggerated wind deflection at long range, that the several inches of spin drift would be lost in the noise, even more so than for the larger caliber bullets that have less relative wind deflection.

Hornady .510 caliber 750 grain Amax

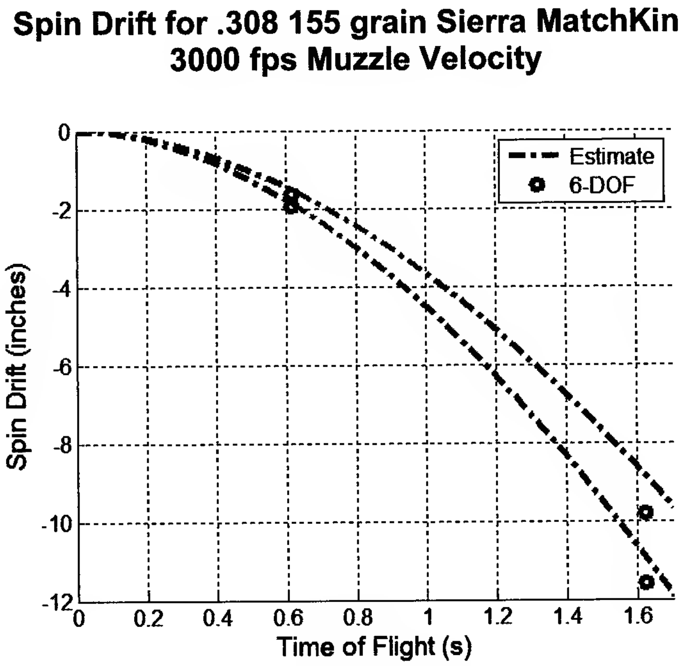
The final data set used in the creation of Equation 6.1 is actual fired data, as recorded by a Doppler radar unit for a .510 caliber 750 grain Hornady Amax out to 2500 yards. At a muzzle velocity of 2690 fps, this bullet goes subsonic at around 1500 yards (~2.6 seconds tof), yet Equation 6.1 continues to match the Doppler spin drift data nearly perfectly all the way out to 2500 yards, and 5.7 seconds time of flight. At 2500 yards, the .510 caliber bullet had a measured 81.38" of spin drift, and Equation 6.1 estimates 81.82" for the same range.

Conclusion

I was quite surprised to see how well such a simple equation could capture the complex effects of spin drift, especially at the extended ranges and thru transonic and subsonic flight speeds. I believe that such accuracy is possible because Equation 6.1 uses *derivative quantities* like the gyroscopic stability factor and time of flight which inherently contain many of the complex effects that are proportional to spin drift.

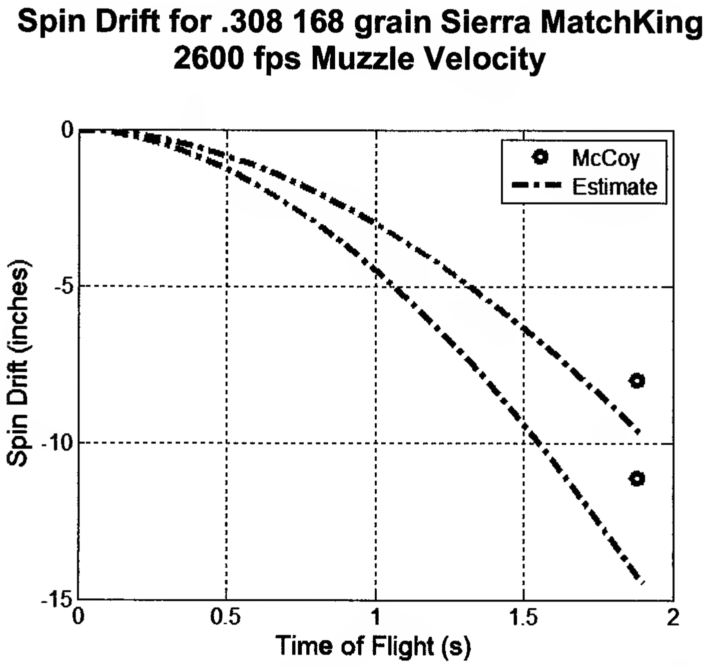
The simplicity of Equation 6.1 makes it very suitable for use in ballistics programs. Time of flight is already computed in ballistics programs. The only additional inputs required are bullet length and barrel twist rate that are needed to compute SG using the Miller Stability formula. The included ballistics program gives the user the option of calculating spin drift by entering the extra variables and checking a box. Equation 6.1 is used by the program exactly as it appears in this Chapter.

The following Figures show the results of Equation 6.6 compared to other sources of spin drift data for each of the bullets discussed above.



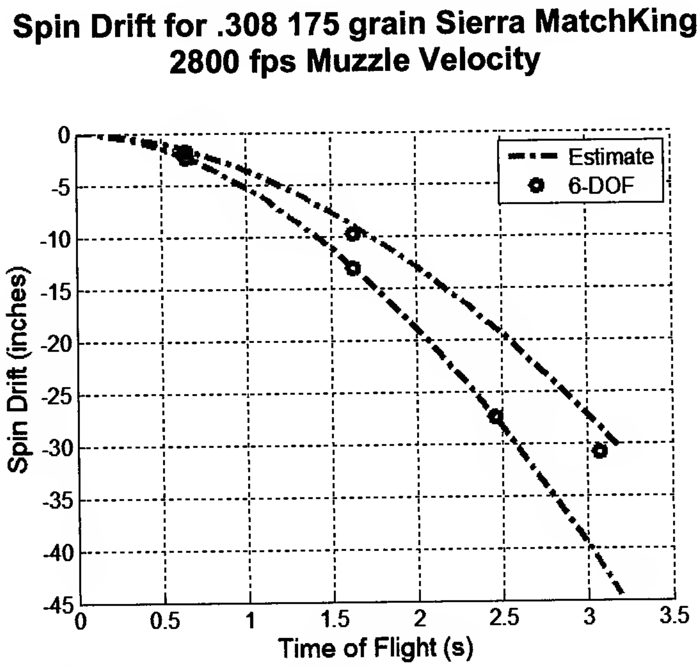
Barrel twist =		1:13"			1:11"		
SG =		1.72			2.40		
		Spin drift			Spin drift		
range	tof	6DOF	Est	error	6DOF	Est	error
500	0.619	1.64”	1.52”	0.12”	1.93”	1.87”	0.06”
1000	1.623	9.82”	8.85”	0.97”	11.58”	10.91”	0.67”

Figure 6.7. The 6-DOF data was generated using a high fidelity simulation. The *estimate* data was generated using Equation 6.1.



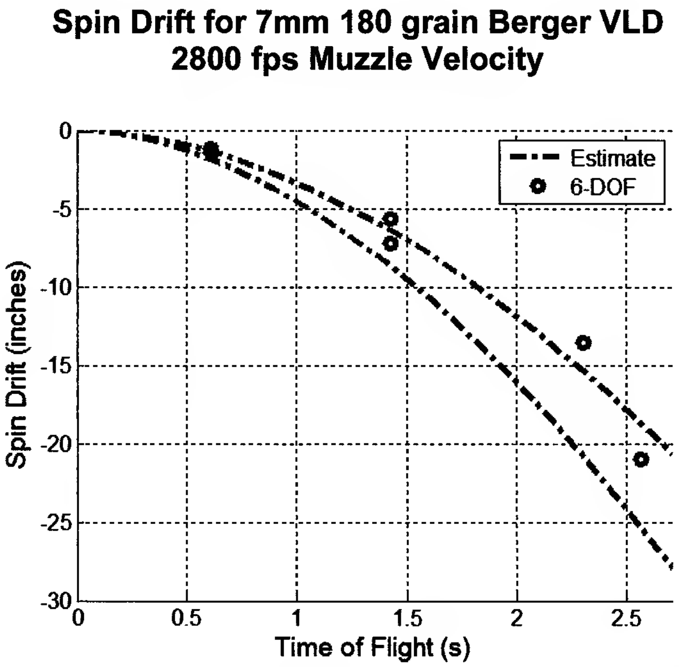
Barrel twist =		1:14"			1:10"		
SG =		1.21			2.38		
		Spin drift			Spin drift		
range	**tof**	**McCoy**	**Est**	**error**	**McCoy**	**Est**	**error**
1000	1.8827	8.0”	9.59”	-1.59”	11.1”	14.24”	-3.14”

Figure 6.8. The McCoy data was obtained from the book: ‘Modern Exterior Ballistics’. The *estimate* data was generated using Equation 6.1.



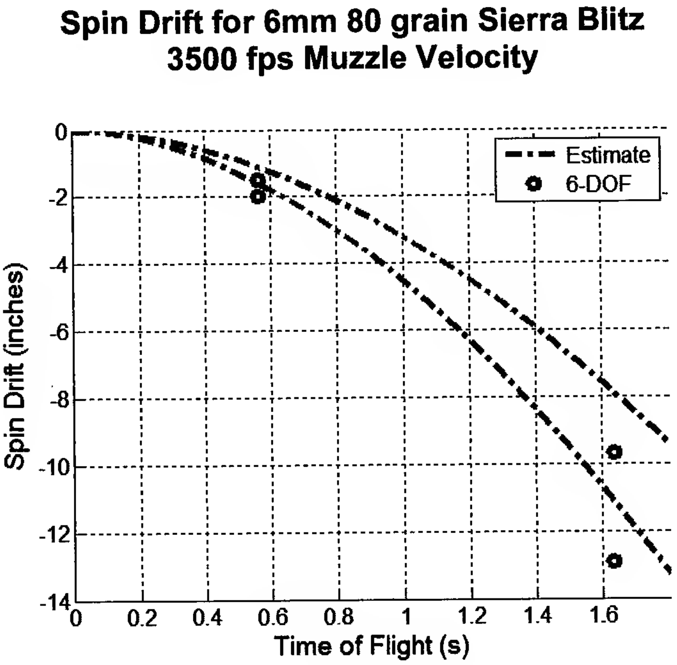
Barrel twist =		1:12"			1:9"		
SG =		1.71			3.04		
		Spin drift			Spin drift		
range	tof	6DOF	Est	error	6DOF	Est	error
500	0.648	1.81”	1.64”	0.17”	2.4”	2.40”	0.00”
1000	1.632	9.85”	8.91”	0.94”	13.08”	12.99”	0.09”
1300	2.460				27.46”	27.52”	-0.06”
1500	3.073	30.84”	28.38”	2.46”			

Figure 6.9. The 6-DOF data was generated using a high fidelity simulation. The *estimate* data was generated using Equation 6.1.



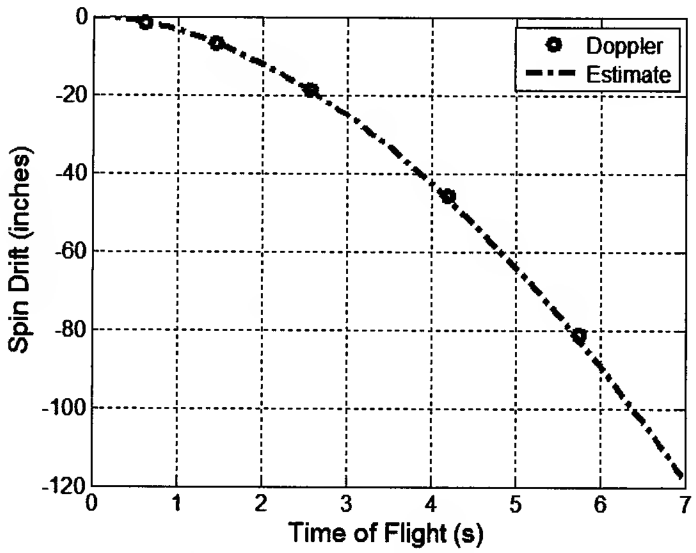
Barrel twist =		1:9"			1:7"		
SG =		1.47			2.42		
		Spin drift			Spin drift		
range	**tof**	**6-DOF**	**Est**	**error**	**6-DOF**	**Est**	**error**
500	0.619	1.64”	1.39”	0.25”	1.93”	1.88”	0.05”
1100	1.6225	9.82”	8.09”	1.73”	11.58”	10.97”	0.61”
1400	2.307	13.54”	15.41”	-1.87”			
1500	2.568				21.04”	25.42”	-4.38”

Figure 6.10. The 6-DOF data was generated using a high fidelity simulation. The *estimate* data was generated using Equation 6.1.



Barrel twist =		1:12"			1:9"		
SG =		1.36			2.41		
		Spin drift			Spin drift		
range	tof	6DOF	Est	error	6DOF	Est	error
500	0.564	1.48”	1.12”	0.36”	1.98”	1.58”	0.40”
1000	1.635	9.69”	7.87”	1.82”	12.90”	11.10”	1.80”

Figure 6.11. The 6-DOF data was generated using a high fidelity simulation. The *estimate* data was generated using Equation 6.1.



Spin Drift for .510 caliber 750 grain Hornady Amax 2690 fps Muzzle Velocity

Barrel twist =		1:15"		
SG =		1.47		
		Spin drift		
range	**tof**	**Doppler**	**estimate**	**error**
500	0.626	1.43"	1.42"	0.01"
1000	1.4543	6.73"	6.62"	0.11"
1500	2.569	18.83"	18.76"	0.07"
2000	4.2038	45.90"	46.20"	-0.30"
2500	5.7444	81.38"	81.82"	-0.44"

Figure 6.12. The Doppler data was for the 750 grain Hornady Amax is highly accurate and can be considered *truth* data. The estimate data was generated using Equation 6.1.

Chapter 7: The Coriolis Effect

The Coriolis Effect occurs as a consequence of the fact that you're shooting from one point to another on a rotating sphere (the Earth). The Coriolis Effect is very minor, and can be disregarded for most practical shooting applications. This chapter is included primarily as a matter of completeness and academic interest. The Coriolis Effect is very subtle but it is deterministic, meaning that it can be predicted and accounted for. In this chapter, formulas are presented that will allow you to calculate and correct for the Coriolis Effect based on your latitude and azimuth of fire.

For target shooters who are always shooting at known distances with sighters allowed, the Coriolis Effect is as inconsequential as spin drift because it's the same for every shot. If you're a long range hunter or tactical shooter who doesn't have the luxury of sighter shots and may find your targets in random directions, you may want to consider the Coriolis Effect, especially when shooting at extended ranges.

Here are some basic facts about the Coriolis Effect:

1. The Coriolis Effect has both vertical and horizontal components which are independent.
2. The horizontal component of the Coriolis Effect is entirely determined by your latitude on Earth, and is unaffected by the azimuth of fire.
3. For latitudes north of the equator, the horizontal component of the Coriolis Effect is always to the right. For latitudes south of the equator, the deflection is to the left.
4. The horizontal Coriolis deflection is minimal at the equator, and grows greater as you move toward the poles.
5. The vertical component of Coriolis deflection depends on your latitude *and* azimuth of fire.
6. Firing east will cause you to hit *high,* and firing west will cause you to hit *low.*
7. When shooting to the north or south, the vertical component of Coriolis deflection is zero regardless of latitude.

Since the horizontal and vertical Coriolis deflections are completely independent of each other, their effects will be presented separately.

The Horizontal Coriolis Effect

As stated above, the horizontal Coriolis Effect only depends on your latitude above or below the equator. The farther you are from the equator, the more severe the Coriolis deflection will be for a given range shot. The formula for calculating the horizontal Coriolis deflection is not very difficult to apply, and is presented below:

$$Horizontal\ Deflection = \Omega \cdot \mathrm{X} \cdot \sin(Lat) \cdot tof$$

Where:

Horizontal Deflection is the Coriolis deflection in feet
Ω is the rotation rate of the Earth (=0.00007292 rad/s)
X is the range to the target (in feet)
Lat is your latitude from the equator (+ for north latitude and – for south latitude)

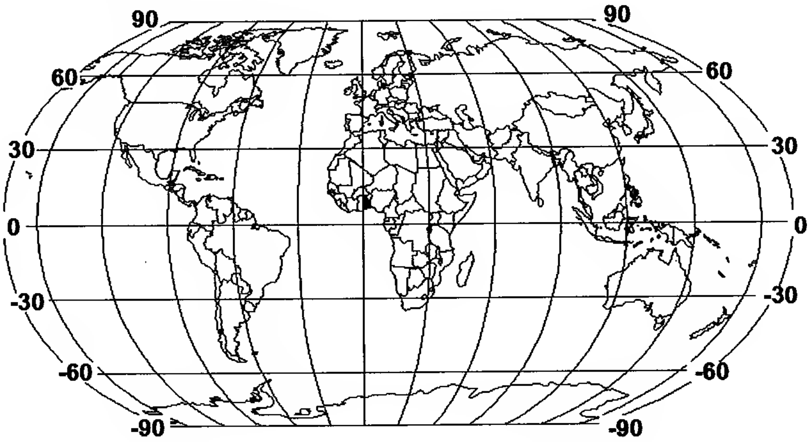
The following example will illustrate the use of the formula for calculating the horizontal component of the Coriolis Effect. The first step is to determine the time of flight from a ballistics program. Now if you know your latitude you have enough information to solve the equation. If you're shooting at 45 degrees north latitude:

$$Horizontal\ Deflection = 0.00007292 \cdot 3000 \cdot \sin(45) \cdot 1.5$$

$$= 0.23\, feet = \mathbf{2.8\ inches}$$

A positive (+) result means the drift is to the right, where as a negative (-) answer would indicate a deflection to the left. If you were at 45 degrees *south* latitude, the deflection would be exactly -2.8 inches (left).

For shooters who mostly stick to a given local area, the horizontal Coriolis Effect will always be the same at a given range. However, when traversing great amounts of latitude (north-south), the effect should be considered. Traveling east-west has no effect on Coriolis deflection. A shooting team that travels from Australia to the US might want to consider the Coriolis Effect on their wind zeros. Australia is pretty far below the equator and the US is in the north. The Australian shooters 1000 yard *no wind* zero is making up for about 2.8" of *left* deflection. If he comes to the US in the middle of the northern hemisphere and shoots at 1000 yards in *no wind* conditions, not only is the 2.8" of *left* deflection not present, but there will be about 2.8" of *right* deflection. The result would be an impact just over 5" (1/2 MOA) to the right of his *southern hemisphere* no wind zero.



Location	Approximate Latitude
USA	25°-50 ° N Lat
Europe	40 ° -60 ° N Lat
Iran, Iraq & Afghanistan	25 ° -40 ° N Lat
Australia	15 ° -40 ° S Lat
New Zeland	35 ° -45 ° S Lat

Figure 7.1. Map showing lines of latitude.

A more likely reality is that the rifle and sights will be bumped around too much during the long transit around the globe and a new *no wind* zero will have to be established at the new location anyway.

The Vertical Coriolis Effect

The vertical component of the Coriolis deflection is also known as the Eötvös Effect, and it's a little more complicated because it involves the azimuth (direction) of fire as well as the latitude (location) of the shooter. Figure 7.2 shows a compass rose with azimuth labeled starting at zero with north and increasing clockwise. Technically you want to use the azimuth relative to *true* north, not *magnetic* north, when calculating Coriolis deflection. However using a magnetic compass will get you close enough considering the minimal scale of the effect.

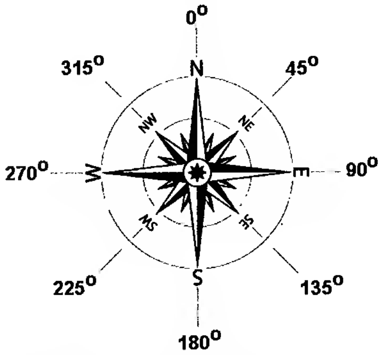


Figure 7.2. Compass rose showing azimuth angles.

The vertical Coriolis deflection is at a maximum for azimuths that are parallel to and near the equator. The vertical Coriolis Effect is an acceleration like gravity except that it depends on your latitude and azimuth of fire. Since the Coriolis Effect is acceleration, you can account for it by scaling the effect that gravity (which is also acceleration) has on bullet drop. The formula below allows you to calculate a *gravity correction factor* that you can use to modify your predicted drop at any range to account for the vertical effect of Coriolis acceleration. The formula for the vertical correction factor is:

$$f = 1 - \frac{2 \cdot \Omega \cdot MV}{g} \cos(Lat) \cdot \sin(Az)$$

Where:

f is the gravity correction factor
Ω is the rotation rate of the Earth (=0.00007292 rad/s)
MV is the muzzle velocity
g is the acceleration of gravity (32.2 ft/s^2)
Lat is your latitude from the equator (+ for north latitude and – for south latitude)
Az is the azimuth of fire (clockwise from north)

f is called a *gravity* correction factor, but you can use it as a *drop* correction factor. The way to account for the vertical Coriolis acceleration at long range is to scale the effect of gravity, which is the same as scaling the drop by the same amount. The following example will illustrate the use of the vertical Coriolis correction factor.

Consider the same 155 grain .308 caliber bullet fired at 3000 fps. The trajectory is zeroed at 100 yards, and there is -307" of drop predicted at 1000 yards before accounting for the Coriolis effect. If the shot is directed due east at 45 degrees north latitude, what will be the *corrected* drop?

The first step is to calculate the gravity correction factor f.

$$f = 1 - \frac{2 \cdot 0.00007292 \cdot 3000}{32.2} \cos(45) \cdot \sin(90)$$

$$f = 0.9904$$

The gravity correction factor of 0.9904 is now multiplied by the basic gravity drop of -307" to arrive at the *corrected* drop:

-307"*0.9904 = -304"

As you can see, the bullet drops 3" *less* when shooting east. If the direction (azimuth) of fire were reversed to west, the previous example would be exactly the same except the azimuth would be 270 degrees instead of 90. The result would be a correction factor of 1.0097, and a resulting corrected drop of -310" which is 3" *more* than the uncorrected drop. In conclusion, you could have +/- 3" of vertical deflection from Coriolis just by shooting different directions. If you obtain a 1000 yard zero shooting east, then turn west, you will have 6" of additional drop from Coriolis.

The vertical Coriolis Effect is potentially more troublesome than the horizontal component because of the directional sensitivity. In other words, in order to incur a drastically different amount of *horizontal* deflection, you have to traverse a great deal of the planet (like the Australian shooting team in the previous example). However, in order to incur the maximum *penalty* or *error* from the *vertical* Coriolis Effect, all you have to do is shoot two shots back to back in opposite directions (east-west then west-east). Shooting in different directions is much more common for an individual shooter than shooting at drastically different latitudes. Another way to look at it is that as long as you stay in the same hemisphere, you will only have horizontal deflection in one direction. However, the vertical deflection can go from + to – by just shooting in opposite directions.

As a final example of the Coriolis Effect, we'll consider a very long range shot of 1500 yards with a 300 grain .338 caliber bullet fired with a muzzle velocity of 2800 fps. Without accounting for the Coriolis Effect, the predicted drop for this bullet is about -800". For a shot that's fired due east at 30 degrees latitude (somewhere in Texas), the gravity correction factor will be 0.989, and the corrected drop will be -791". In this case, the penalty for not accounting for the Coriolis Effect is 9", which is just over ½ MOA (2 clicks) of scope adjustment. The same 9" of error would occur if a shot is 15 fps faster than average. In other words, the vertical difference between shooting east vs west in Texas has the same effect as a +/- 15 fps difference in muzzle velocity at 1500 yards in this example.

Now let's consider the horizontal component of the Coriolis Effect. The time of flight to 1500 yards is about 2.36 seconds, so the average velocity is 4500 (ft) / 2.36 (sec) = 1907 ft/sec. Plugging this into the formula for horizontal deflection yields 4.7" of horizontal deflection. To put this in perspective, a crosswind of just 0.35 mph will deflect the bullet by the same amount at that range. Also note that for a 1:10" twist barrel, the spin drift will be about 16".

For this extended range example, the Coriolis Effect results in an impact that's 9" high and 4.7" to the right. On one hand, that seems like a serious enough error to consider, depending on the size of the target. On the other hand, the effect is overshadowed by other non-deterministic uncertainties like wind deflection and muzzle velocity uncertainty. Because of the relatively minor effect of Coriolis deflection, many long range shooters understandably choose to ignore it. For many practical shooting situations like long range hunting, opportunities can have a time limit. If you spend too much time calculating Coriolis Effects, you may not even get a chance to make a shot. If you do have enough time to measure and account for the Coriolis Effect and you've got a good handle on the other more important variables involved in the shot including level sights, there's no reason to ignore the Coriolis Effect.

One clever way to deal with Coriolis and spin drift is to choose the direction of barrel twist so that the spin drift is in the opposite direction as the (horizontal) Coriolis deflection. For example, in the northern hemisphere, the (horizontal component of) Coriolis effect is to the right. If you shoot a right (clockwise) twist barrel, then Coriolis and spin drift will compound. However, if you choose a left twist barrel, then spin drift will be to the left. The effects won't *exactly* offset each other (spin drift is about 5 times greater than Coriolis) but from an error budget point of view, it's better to have an offsetting effect than a compounding effect.

Chapter 8: Using Ballistics Programs

There is a vast array of commercial ballistics programs available in the sporting arms industry. A good ballistics program is an absolute necessity for successful long range shooting, and it doesn't have to be complicated!

Ballistics programs allow you to calculate bullet drop, wind deflection, time of flight, kinetic energy, and many other details of the bullet's performance. The ability to accurately predict the bullets downrange trajectory is important to hunters and tactical shooters who need their first shot to be a hit. In essence, *a ballistics program is the tool that's used to account for all of the deterministic variables in long range shooting.*

Competition shooters don't require extremely accurate trajectory predictions because they're allowed *sighters* to get zeroed on the target before *record shots* are fired. That doesn't mean that ballistics software is useless for target shooters. The ballistics programs can also be used to study the comparative performance of two different rounds to see which one is better. This is a capability that all shooters can use to make more informed decisions.

Features of Ballistics Programs

The minimum required inputs for a ballistics program are: bullet caliber, bullet weight and BC, muzzle velocity, atmospherics including wind speed and direction, sight height and zero range. This is all that's required to calculate a basic trajectory. Other variables include: moving targets, moving shooter, uphill/downhill shooting, Coriolis drift, spin drift, lateral sight offset, cant angle, kinetic energy, recoil energy, libraries of bullets, reloading information, etc. Of course these extra features make it possible to calculate trajectories for any conceivable shooting scenario, but they also complicate things for the shooter who's just looking for a basic solution. Extra features also come at an extra price. The one thing to keep in mind is that *the expensive programs are not more* ***accurate*** *than the inexpensive programs.* The accuracy of the solution depends on the accuracy of the inputs you give it, not how many dollars the program costs.

There are several unique types of solvers currently used for small arms ballistics. No matter how many bells and whistles are surrounding the solvers, one thing is true for all of them: *the trajectory predictions are only as accurate as the inputs*. This should come as no surprise, but I decided to repeat it anyway.

All of the different solvers are just various mathematical approaches to solving Newton's fabulous equations of motion. Back in the days before computers were so widely available and powerful, analytic solutions were required to solve the equations of motion. Some modern programs still use these old solvers because of their simplicity. Since computer processors have found their way into everyone's home and most people's palms (cell phones and PDAs), more sophisticated solvers can be employed that actually integrate the equations of motion numerically. Numeric integration is the most accurate way to solve ballistic trajectories, and a numeric solver is what's used in the included software.

The Pejsa solution is an interesting approach to solving trajectories. The simplicity of that solution technique is possible because the velocity (Mach) dependent projectile drag is managed in a very tricky way. Basically, the method requires several sets of coefficients/exponents for different speeds to *cheat* the G1 drag curve into something that looks more like a G7 drag curve. In other words, the program requires several obscure numbers to quantify the bullet (instead of a single BC), so the equations of motion can be solved (simply) in closed form. Personally, I fail to see the practical advantage of this approach over using a standard solution with a single G7 BC. Extensive testing is required to establish the *special coefficients and exponents* for the Pejsa solution so it can be accurate at all velocities. Using a single BC referenced to a representative (G7) standard is much easier for the shooter than establishing unique sets of *special coefficients and exponents* for each bullet to work in the Pejsa solution. Even if one goes to the trouble to establish these obscure bullet parameters, in the end, there's no way to judge the relative ballistic performance of bullets like you can by simply comparing BCs. In my view, *the simplicity of the Pejsa solution method is only possible because the complexity is shifted onto the bullet description, which the shooter is burdened to establish for himself for each bullet at all velocities*. It may be fun and easy for programmers to write a ballistics program with Pejsa's equations. However, since the shooter is stuck with the complexity of establishing the special coefficients and exponents for each bullet. I really don't see this method as the most useful solution for *shooters*.

Using Ballistics Programs

The two basic applications for ballistics programs were mentioned at the opening of this chapter: to predict the bullet's flight path in order to adjust sights and hit targets, and to do comparative performance analysis of various rounds.

There are several ways to get the trajectory data required to hit targets. You can use your home computer to generate ballistics tables, print them out and take them to the field with you. This approach is always a compromise because you can't print out every table you need for every conceivable combination of variables. At a minimum, you print one chart that reflects the expected nominal conditions you plan to shoot in. You could also overkill the situation by printing a whole binder of charts that covers every shooting situation you might encounter. Somewhere in between is a happy medium. The advent of inexpensive palm devices (PDAs) offers a terrific capability to long range shooters. This device allows you to enter the exact field conditions that are present, and returns a firing solution for that exact shot. No need to carry printed tables and interpolate thru all the generic data. With a PDA, you have the flexibility to input the current conditions so the program can account for them in *real time.*

For those who want to use ballistics programs to compare the performance of various rounds, it's ok to leave most of the inputs at their default values since you're just looking for the *difference.* For this kind of work, the PC based programs are more convenient than the PDAs with their small screens. When using ballistics programs to analyze performance, you input data for the first round, calculate the trajectory and note the particular outputs that are interesting for the comparison. For example, you might be interested in comparing the relative wind deflection of a low BC bullet at high speed, compared to a high BC bullet at low speed. You would input the first set of data, calculate the trajectory, and note the level of wind deflection at the range of interest. Now input the data for the second round, leaving all other variables the same, calculate the trajectory and note how the wind deflection compares to that of the first round. In this kind of application, it's not necessary to have all the environmental inputs correct. Since you're looking at relative performance, the analysis will apply on any given day.

Of course these are just the most common uses of ballistics programs. There are countless other questions that can be answered and ideas to be explored with a ballistics program.

For example:

- My scope only has 30 MOA of vertical adjustment available. How far out could I zero this rifle? How much extra range is possible with a 20 MOA tapered scope base?
- How far out does my bullet retain at least 1000 foot pounds of kinetic energy? This can be important in a hunting situation where a bullet needs a certain amount of energy to expand properly.
- I'm shooting a 6mmBR in a long range rifle match. How much crosswind does it take to blow me out of the 20" 10 ring at 1000 yards?
- My shooting buddy says that 225 grain bullets drop less than heavier bullets from his .338 Lapua Magnum at all ranges. Is that true, or is

he simply afraid to admit that the recoil of heavier bullets is just too much?

- The extreme spread of my muzzle velocities is 25 fps. How much of a difference in vertical impact will this cause at 1000 yards?

These questions and many others can be explored using any standard ballistics program. The following is a short example to show how the included ballistics program can be used to help you hit targets at long range.

Let's say you've got an incredibly accurate load for your 7mm Remington Magnum hunting rifle. It shoots under 1 MOA groups all day long with Berger's 7mm 180 grain VLDs. Now this rifle has been reliable for years out to a comfortable range of 200 yards; a chip shot for this rifle where no real sight corrections are required to counter the effects of drop or wind deflection. Now let's say you want to take this rifle on an elk hunt where you can potentially expect shots up to 800 yards. You know that additional information and equipment is required to prepare for the hunt, but what do you need? At a minimum, you need a chronograph, a rangefinder, a ballistics program and a working knowledge of how to use it.

The chronograph is used to measure the speed of the bullets, which is an essential input required by the computer program. You know you will be hunting in a place that's 5,500 feet above sea level in the summer. You can use this information to find out what the average atmospheric conditions (temperature, pressure and humidity) will be. Table 8.1 lists the standard atmospheric pressure for altitudes up to 10,000 ft. Pressure is the variable that's most strongly related to altitude. Temperature and humidity are more related to the season and time of day for any given altitude.

Altitude (feet)	Pressure (inHg)
0	29.92
1000	28.86
2000	27.82
3000	26.82
4000	25.84
5000	24.90
6000	23.98
7000	23.09
8000	22.23
9000	21.39
10,000	20.58

Table 8.1. Standard atmospheric pressure

This basic research is required before an accurate table can be generated. Once you know all the inputs, you can enter them into the program and record the outputs.

Let's say you acquire a chronograph and fire 10 shots of your proven accuracy load across it and find the average velocity is 2965 fps. After some quick internet research (or referring to Table 8.1 or the Appendix) you can find out that the standard atmospheric pressure at 5,500 feet is 24.43 inches of mercury, and the average summer temperature is 55 degrees Fahrenheit. The humidity is a guess for any given day, but it's the least important atmospheric variable to consider, so go with 50%. In the past, you would have to use the uncertain and inconsistent G1 BCs that the bullet makers provided, which could add a lot of potential error to your trajectory prediction. However, the highly accurate, experimentally determined G7 BCs presented in the book:

Ballistic Performance of Rifle Bullets solves the problem of uncertainty, at least for BCs.

The 7mm 180 grain VLD has a G7 BC of 0.337 lb/in^2. There's one more easy step, and that's to measure how far the centerline of your scope is above the centerline of the rifle barrel. You now have enough information to enter into the ballistics program and calculate a baseline trajectory for your hunt. Figure 8.1 shows the program with all the proper inputs, and the output in 100 yard increments.

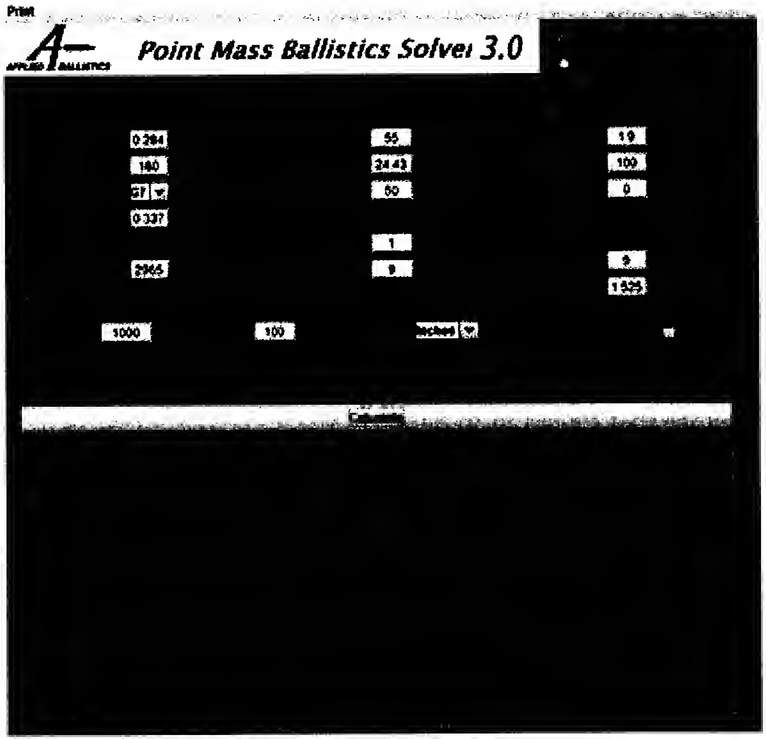


Figure 8.1. Ballistics program showing inputs and outputs.

The raw output of the program is useful as is, but may need to be manipulated for specific purposes. For example, it may be convenient to convert the drop from inches to Minutes Of Angle (MOA) in order to make scope adjustments easier. Also, if you want to know the Kinetic Energy (KE) of the bullet as it goes down range, you have to calculate it from the bullets weight and velocity (See Chapter 11 or the Appendix for an example of calculating KE). All of the raw information is there, it's just a matter of putting it to use. The drop data can be printed on a small card, laminated and slipped in your wallet, or taped to a piece of shooting equipment that you know will be with you in the field. All you have to do on site is measure the range to the target, look at your table to determine drop and adjust the scope to the proper elevation. There's still the minor hassle of judging the wind and executing a well-placed shot, but what fun would the hunt be if the program aimed and fired the rifle for you!?

Of course the above example is a little simplified. There are a lot of various aspects of your equipment and technique that have to be right in order to score successful hits at long range which are discussed elsewhere in this book. The point of the previous example was just to illustrate the basic information required by the program, how to get it, and how to use the results.

The static print out is a valuable thing to have in the field. It's not as flexible as a PDA which allows you to enter the exact variables of the day, but there are no batteries to go dead or circuits to get wet in a laminated card. In short, it's a reliable way to carry the essential information with you.

There will certainly be variables present that are a little different than what you anticipated. In those cases, you can use your judgment to determine what effect a 5 degree difference in air temperature would have on your trajectory for example. Your judgment of these things will become more accurate as you play with the program and notice the effect that different variables have on trajectory. The important thing is that the information you take in the field is an accurate starting point. One thing you can do to limit the number of tables you need for wind deflection is to print out the wind deflection for a 1 mph crosswind. If you have a 3 mph crosswind in the field, simply multiply the deflection in your table by 3. This saves you from needing tables for each possible wind speed.

All of this discussion about ballistics programs begs the question: how accurate can the output of a ballistics program be? The next section will explore that question in depth.

Validating Ballistics Programs

A frequently asked question is: How accurate is a particular ballistics program? There are several approaches to answering this question. One is to compare the outputs of the program to the outputs of other programs, given the same inputs. If the results match, you can at least have confidence that your program is consistent with others, but are they really *accurate*? Can any of them truly predict the trajectory of a bullet in the real world? This question intrigued me for years until I was finally compelled to put the math to the test. Now there are many different ways to conduct experiments to test the accuracy of a ballistics program, all with different variables and uncertainties. The trick is to devise an experiment that eliminates as many variables as possible. The following is the approach I took to validate the Point Mass ballistics program that's included with this book.

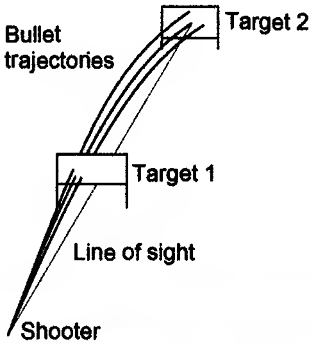
As stated earlier, the outputs of a program can only be as accurate as the inputs. Muzzle velocity and atmospheric conditions are readily measured with commercial instruments like the CED Millennium chronograph, Kestrel 4000 pocket weather meter, and Nikon 1200 yard laser rangefinder used for this experiment. Typically, the BC is the hardest thing to be sure of. Naturally I used my measured G7 BC for the bullets used in the test. It's interesting to note that the BCs are calculated from measured time of flight data using a ballistics program with a standard solver. In other words, the BCs are established using measured *time of flight*, and the current experiment will demonstrate how accurately a ballistics program can use that G7 BC to predict *drop*, which is what we actually care about for practical purposes.

A typical approach to observing drop is to zero a rifle at close range, and see how much scope elevation adjustment is required to hit the aiming mark at a longer range. There are at least two big flaws in this approach. First of all, the accuracy of the scope adjustments is an uncertain link between how much you think the bullet drops compared to how much it actually drops. In other words, many scopes have inaccurate and/or inconsistent adjustments or reticles so that when you dial or hold over 30 MOA of elevation, your point of aim might actually move 29 MOA, or 31 MOA. This kind of error is minor for most practical shooting situations, but for the purposes of scientific experimentation it's huge, and must be eliminated from the equation.

A better approach is to zero high at short range, then turn the rifle to a long range target and shoot another group without adjusting the sights. This is a much better approach because you eliminate the uncertainty of scope adjustment from the equation. This approach is still limited though because you have two different groups of shots. What if something was different about the long range group? A different average muzzle velocity for example? Even if you're just turning the rifle to aim at the distant target immediately after shooting the short range one, it's possible that the rifle's point of impact could be affected slightly by variables outside of your knowledge and control. Admittedly, if the experiment were done carefully the uncertainty would be minimal, but uncertain none-the-less.

The only way to be absolutely certain that you're measuring bullet drop directly is to capture the same group of shots at two ranges. This is done by zeroing the rifle at long range and mounting a thin paper target *in the path* of the bullets at some point between the shooter and the distant target (without blocking the line of sight to the distant target). Figure 8.2 includes a conceptual sketch and a picture of the test set-up showing the rifle, chronograph, a target at 187 yards, and one at 991 yards. Careful surveying of the target locations in relation to the line of sight is required in order for this test to work. The basic procedure is as follows:

1. Start with the rifle zeroed at the distant range.
2. Use a level to draw a horizontal reference line on Target 1.
3. With the rifle in firing position and bolt removed, place the crosshairs on Target 2. The line of sight is beneath Target 1.
4. Direct a surveying partner to measure the distance from the horizontal reference line on the first target down to the line of sight.
5. Use a plumb line to place a vertical reference line on Target 1 directly above the line of sight.
6. Without moving the rifle from its original position, fire a group of shots using the center of Target 2 as the aim point. If Target 1 is in the right place, the shots will print on both targets.
7. The vertical and horizontal reference lines on Target 1 can be used to determine where the bullets were at that range, in relation to the line of sight.
8. The bullet impacts in Target 2 can be measured from the center of that target since that was the aim point.



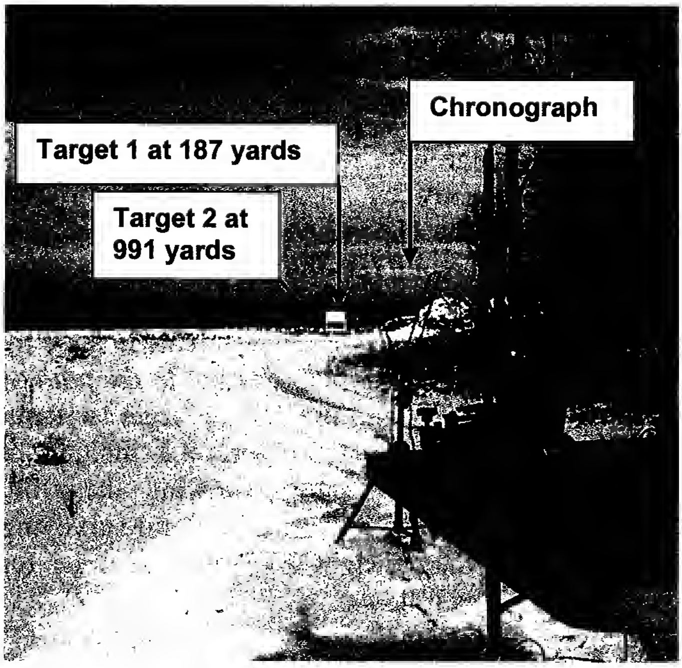


Figure 8.2. Set up for the two-target drop test.

This is the procedure that I used to acquire the actual bullet drop data. With proper surveying, the trajectory of a bullet in relation to the line of sight can be measured very accurately. Of course, there are uncertainties involved with every measurement. The particular uncertainties of this experiment will be examined later.

.260 Remington

For this test, two rifles were used to produce shot groups at the two distances. The first rifle was a .260 Remington match rifle firing 6.5mm 142 grain Sierra MatchKing bullets.

The location of each shot on the 187 yard and 991 yard targets is shown in Figure 8.3. The top part of Figure 8.3 shows the shot group at 187 yards. You can see that the shots landed about 49 inches above, and a little to the left of the line of sight. The bottom plot in Figure 8.3 shows the predicted and actual bullet impacts at 991 yards. The exact X and Y location of each shot is tabulated in Figure 8.3, along with the error between the predicted and actual impacts at 991 yards.

The *predicted* impacts at 991 yards were generated as follows:

1. The X (horizontal) location was predicted by assuming constant lateral dispersion. In other words, shot #1 which landed 1.00 inch left of the line of sight at 187 yards, is expected to strike 5.3 inches to the left at 991 yards (991 yards/187 yards = 5.3).

2. The predicted locations of the Y (vertical) strikes of the bullets were arrived at using the included ballistics program. The program was used to generate a trajectory for each shot that's above the line of sight at 187 yards by the measured amount. The amount of bullet drop predicted at 991 yards for that trajectory is the *predicted* Y location of the bullet strike. The muzzle velocity for each shot was used in the program to account for its effect on each shot's expected vertical impact point.

The atmospheric conditions during this test as measured by a Kestrel 4000 are given later in this chapter in Table 8.3. As usual, the wildcard was the wind. The wind was quite steady at 8 MPH directly from 6 O'clock. Of course wind conditions are never *precisely* consistent for a group of shots. Fortunately for this experiment, head and tail winds have a relatively minor effect on bullet drop. The 8 MPH tail wind only lifts the vertical impact of the bullet by less than 2" at 991 yards compared to a no wind shot. This was accounted for when generating the predicted impact points with the ballistics program. As will be demonstrated later in the section on uncertainty, an error of +/- 2 MPH of tail wind translates into +/- 0.4" of error in the predicted impact at 991 yards. Of course there is the potential complication of a vertical wind component that could deflect the bullet up or down. No effort was made to measure the presence or magnitude of a possible vertical wind component for this test. Given the flatness of the land on the test range[11], it would be difficult for much of a vertical wind to develop, but I acknowledge the potential error that it presents and accept it as an uncertainty of the test.

Turning our attention back to Figure 8.3, there are a lot of interesting observations to be made about the two shot groups and how the predicted impacts compare to the actual impacts at 991 yards.

Notice that shots #4 and #5 were slower than average. You can see in the predicted and actual shot groups at 991 yards that shots #4 and #5 are proportionally lower in the group than they were at 187 yards. This simply illustrates that shots with lower initial velocity will have more drop at long range.

It's obvious that the actual shots landed a significant distance to the right of where they were predicted to hit based on their locations at 187 yards. There are several possible explanations for this. If you recall Chapter 6, then spin drift should come to mind as a potential culprit for the displaced shots. According to the spin drift equation, these bullets are expected to have about 6" of spin drift between 187 and 991 yards. That prediction compares remarkably well with the observed displacement of the shots (average of 5.6" horizontal displacement). However, there's another possibility for the displacement; wind. The 8 MPH wind was judged to be a direct tail wind at the firing location, but if that wind was just 10 degrees off of a direct tail wind, it would produce over 8" of horizontal deflection between 187 and 991 yards.

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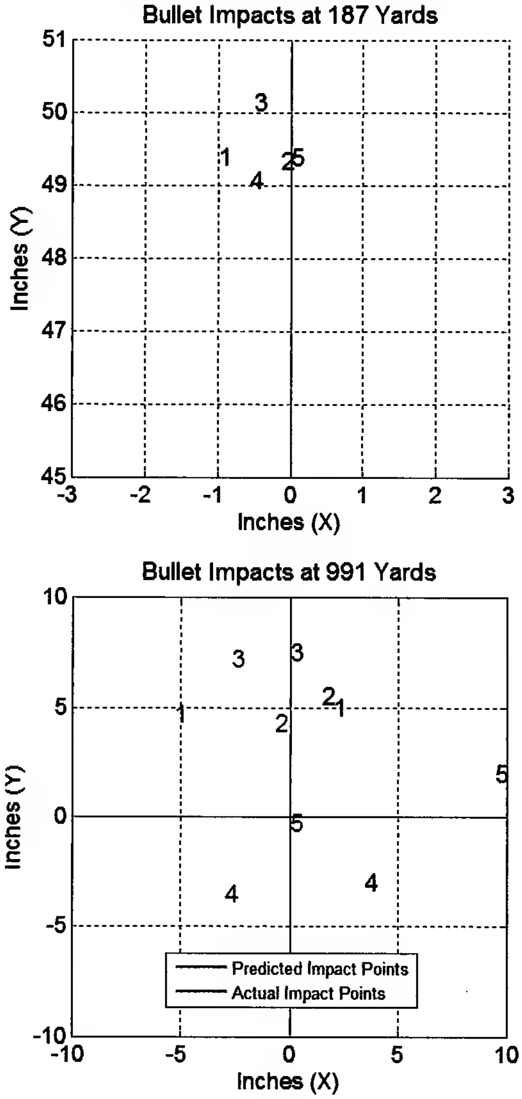
[11] This particular test was conducted at the 1000 yard Reade Range in Allemans, PA.

.260 Remington: 142 grain Sierra MatchKings



Shot	Velocity[12]	187 yards		991 yards				Error	
				Predicted		Actual			
		X	Y	X	Y	X	Y	X	Y
1	2914	-1.00	49.39	-5.3	4.7	2.0	5.0	7.3	0.3
2	2914	-0.13	49.33	-0.7	4.3	1.5	5.5	2.2	1.2
3	2907	-0.50	50.14	-2.7	7.2	0.0	7.5	2.7	0.3
4	2883	-0.56	49.08	-3.0	-3.5	3.5	-3.0	6.5	0.5
5	2890	0.00	49.39	0.0	-0.3	9.5	2.0	9.5	2.3
Average:								5.6	0.9

Figure 8.3. Results for the .260 Remington drop test.

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[12] Velocity is corrected to be actual muzzle velocity, accounting for the 6 fps the bullets lose between the muzzle and chronograph.

Although I would like to say that I have measured spin drift directly, it just wouldn't be a responsible statement to make in light of the uncertainty produced by wind direction. This experimental set up could be used to measure spin drift, but it would have to be done in the total absence of any wind in order to be valid. Rifle cant (tilt) may seem like a reason for the horizontally displaced shots, but it's not. The horizontal displacement of shots due to rifle cant is proportional with range, meaning that if cant was present (no doubt there was some amount present) it's accounted for in the way the horizontal location of the shots were predicted at 991 yards.

It's interesting to speculate about the possible causes of the ~6" of horizontal displacement, but it's a small issue given the objective of the experiment, which is to measure the ***bullet drop***.

Looking again at the table in Figure 8.3, you can see that there is an average error of only 0.9" in the vertical location of the bullet impacts. In other words, *based on the bullet's initial velocity and the location of the shots at 187 yards, the ballistics program predicted where those shots would impact at 991 yards within 0.9"*. This is an extremely encouraging result because it confirms that ballistics programs with accurate inputs can indeed be used to predict trajectories with incredible accuracy when all the variables are properly accounted for. Later in this chapter, an analysis of this test's uncertainties will show 0.9" to be within the expected error bars of the experiment.

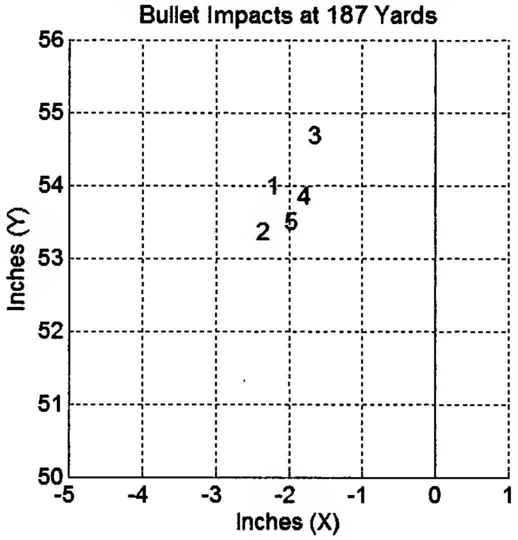
Keep in mind that the G7 BC of the bullets used in this test were established beforehand, and they were not *tweaked* to match the results of the experiment.

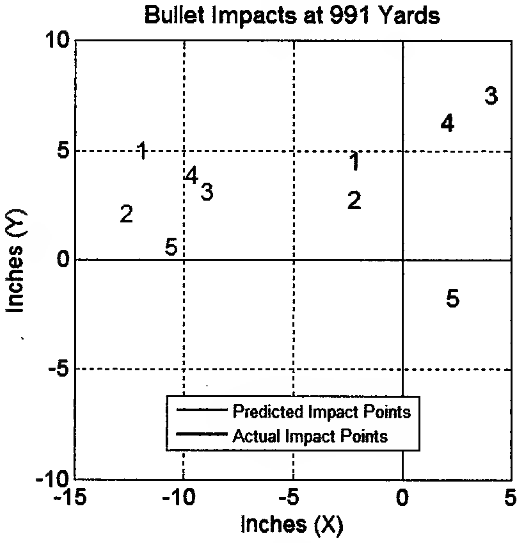
.308 Winchester

Another rifle/bullet combination was tested on the same day, with the exact same set-up as the .260 Remington. The second rifle is also a match rifle, this one chambered for .308 Winchester. In fact, it's the same Palma rifle I used to win the US National Palma Individual Trophy earlier that year (2008). The bullets used for the test are the same bullets used in to win that Championship; Berger .30 caliber 155.5 grain FULLBORE bullets. The results of the Palma rifle drop test are shown in Figure 8.4.

One thing that's immediately obvious about the results for the .308 is the same displacement of shots to the right at 991 yards. This time it's an average of 11.6" horizontal deflection between where the shots were expected, and where they actually arrived on the paper. According to the spin drift equation, these .308 bullets are expected to have about 9" of spin drift between 187 and 991 yards. Although this is close to the observed 11.6" displacement, it's impossible to know if it's actually from spin drift or a small component of crosswind.

.308 Winchester 155.5 grain Berger FULLBORE





Shot	Velocity[13]	187 yards		991 yards				Error	
				Predicted		Actual			
		X	Y	X	Y	X	Y	X	Y
1	3003	-2.31	54.00	-12.2	5.0	-2.5	4.5	9.7	-0.5
2	3005	-2.44	53.37	-12.9	2.1	-2.5	2.8	10.4	0.7
3	2979	-1.75	54.69	-9.3	3.1	3.8	7.5	13.1	4.4
4	3001	-1.88	53.87	-10	3.9	1.8	6.3	11.8	2.4
5	2995	-2.06	53.51	-10.9	0.6	2	-1.8	12.9	-2.4
							Average:	11.6	0.9

Figure 8.4. Results for the .308 Winchester drop test.

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[13] Velocity is corrected to be actual muzzle velocity, accounting for the 8 fps the bullets loose between the muzzle and chronograph.

Another thing that's apparent is that the predicted and actual .308 strikes don't map as well as the .260 shots did. The error between predicted and actual vertical impact at 991 yards for the .260 shots was from 0.3" to 2.3", a spread of only 2". For the .308 shots, the error is from -2.4" to + 4.4", a spread of 6.8". I have a couple of theories regarding this observation. First, it could have been the wildcard of the potential unknown vertical wind kicking up. A different theory can be illustrated with shot#3.

Shot #3 was the highest shot in the group at 187 yards, but had the slowest MV by far, around 20 fps below the average. Due to the low measured speed of this shot, the ballistics program predicts that it should fall back down into the group at 991 yards. However, at 991 yards, that shot is still the highest in the group, and has the most error of any of the shots, hitting 4.4" higher than predicted. One likely explanation is that the measured velocity was inaccurate for that shot. If the trajectory of shot #3 is predicted using a muzzle velocity closer to the average 3000 fps and its known location at 187 yards, the predicted impact at 991 yards would have been 8.0" above the line of sight, which is only 0.5" above where the shot actually hit. This shot strongly suggests a chronograph error. Chronographs are known to be sensitive to light conditions, and the day of the test was sunny with passing clouds.

Regardless of the spread of error for the .308, the average vertical impact was only 0.9" above the predicted vertical impact. It's interesting to note that if the suspicious shot #3 is disregarded, the average drop error is less than 0.1" for the remaining four shots at 991 yards.

There is another possible reason for the bullets to have different amounts of vertical impact error: BC variation. A particular bullet design will have a certain *nominal* BC, but it's possible for each individual bullet to have slightly different BCs from dimensional differences like tip diameter. I don't know how much of the vertical error in these tests is due to imperfect chronograph readings, how much is due to imperfectly matched BCs, and how much is simply random dispersion. No modifications were made to the bullets to uniform their BCs, they were loaded and shot right out of the box.

Despite the relatively minor imperfections of this test, I believe it was very successful at proving that ballistics programs can indeed be used to predict extremely accurate trajectories for bullets in the real world. One of the most exciting things is the knowledge that it didn't take some ultra sophisticated software program running for hours on a super computer to produce such accurate results. The ballistics software program used to generate the predicted trajectories for this experiment is the same exact program that's included with this book! It's simply amazing that this easy to use and free software that runs on any common computer can be used to generate such accurate trajectories. Of course this program isn't really original or unique. It's a standard ballistics program with a typical numeric solver. The outputs agree very well with countless other programs using the same common solvers. The thing that has always limited the accuracy of

Source of uncertainty	Estimated Magnitude of uncertainty	Effect of uncertainty on the vertical impact at 991 yards[14]
Muzzle velocity	+/- 3 fps	+/- 0.6"
Tail Wind Speed	+/- 2 MPH	+/- 0.4"
Vertical placement of the 187 yard target	+/- 0.1"	+/- 0.5"
Bullet BC	+/- 1%	+/- 1.8"
Air Density	+/- 1%	+/- 1.8"
Aiming error	+/- 1.0"	+/- 1.0"
RSS Total Uncertainty:		**+/- 2.9"**

Table 8.2. Approximate uncertainties and their effects on the drop test.

these programs has been the lack of accurate BCs to use in the programs. Now, with just a *common* ballistics program combined with the measured BCs, it's possible for everyone to calculate trajectories as accurate as the ones used in the test described in this chapter.

After a short discussion about the error bounds for this test, I'll present a short example that will allow you to re-create the predicted drop data for the previous experiment.

Uncertainty Analysis

It was stated at the beginning of this topic that my current test set-up is the best way to minimize the errors involved in measuring bullet drop. However *minimized* does not mean *ignored.* Table 8.2 is a listing of the uncertainties involved in the drop test experiment.

As Table 8.2 shows, the combined Root Sum Square (RSS) uncertainty for the bullet drop test set up is +/- 2.9" at 991 yards. That means that as long as the actual bullet impact is within +/- 2.9" of its predicted location, the drop prediction is valid within the resolution of this particular experiment.

There was only one shot out of 10 (shot #3 of the .308 test) that was outside the +/- 2.9" error bar. The fact that the average error for both the .260 and .308 drop tests was only 0.9" at 991 yards is really beating the odds considering all the sources of measurement uncertainty involved in this test.

Re-creating the test predictions using the included software

What good would the ballistics program be if you couldn't use it to its potential? This section will illustrate how the included software was set up and used to produce the predicted drop values that were described in the earlier sections of this chapter. Table 8.3 lists the relevant input variables used to generate the predictions for the drop test.

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[14] These effects are averaged between the .260 and .308. Since the magnitudes of uncertainty were only estimated in the first place, it wouldn't make sense to worry about how the effects are different for the .260 vs the .308.

Variable	Value for .260	Value for .308
Bullet caliber	.264	.308
Bullet weight	142 grains	155.5 grains
Bullet G7 BC	0.301 lb/in^2	0.237 lb/in^2
Sight Height	1.79”	1.91”
Temperature	39.5 °F	39.5 °F
Pressure	28.49 InHg	28.49 InHg
Relative Humidity	60.1%	60.1%
Wind Speed	8 MPH	8 MPH
Wind Direction	6 O’clock	6 O’clock

Table 8.3. Ballistics Program inputs for the drop test.

The one variable that’s not listed in Table 8.3 is the zero range because it had to be altered in order to get the trajectory to the observed height at 187 yards. As an example of the process, consider the first shot of the .308 test. To set up the ballistics program for this shot, enter all of the information in Table 8.3, and the muzzle velocity of 3003 fps. Set the *Range Step Size* to 1 yard. This will allow you to see where the bullet is at 187 yards. Set the zero range at 991 yards to begin with, and click *calculate.* Scroll up to 187 yards, and see how high the bullet was above the line of sight there. For a zero range of 991 yards, the trajectory should be 53.05” high at 187 yards. Now, we know that shot was actually 54.00” high at 187 yards according to the table of data in Figure 8.4.

In order to re-create that exact trajectory, adjust the zero range outward until the trajectory is exactly 54.00” high at 187 yards (because that’s where that shot was observed at 187 yards). This shot turns out to require a zero range input of 999.9 yards to result in the bullet being 54.00” high at 187 yards. Remember, the actual zero range is arbitrary for each shot. What’s important is that the program is forced to match the observed height at 187 yards, and then you see how much it falls below that at 991 yards. If all of the inputs are correct, this shot results in an impact that’s 5.00” high at 991 yards. The actual bullet hit 4.5” high, meaning that there is an error of 0.5” of drop for this shot. Figure 8.5 is a screenshot of the ballistics program showing the inputs and trajectory at the key ranges (0, 187, and 991 yards). The procedure can be repeated for each shot. Just remember to enter the correct muzzle velocity, and iterate until you find the correct zero range input to match the trajectory at 187 yards.

This is certainly a non-standard way to use a ballistics program. Typically, you would just enter a normal zero range, and look at the resulting trajectory on either side of it.

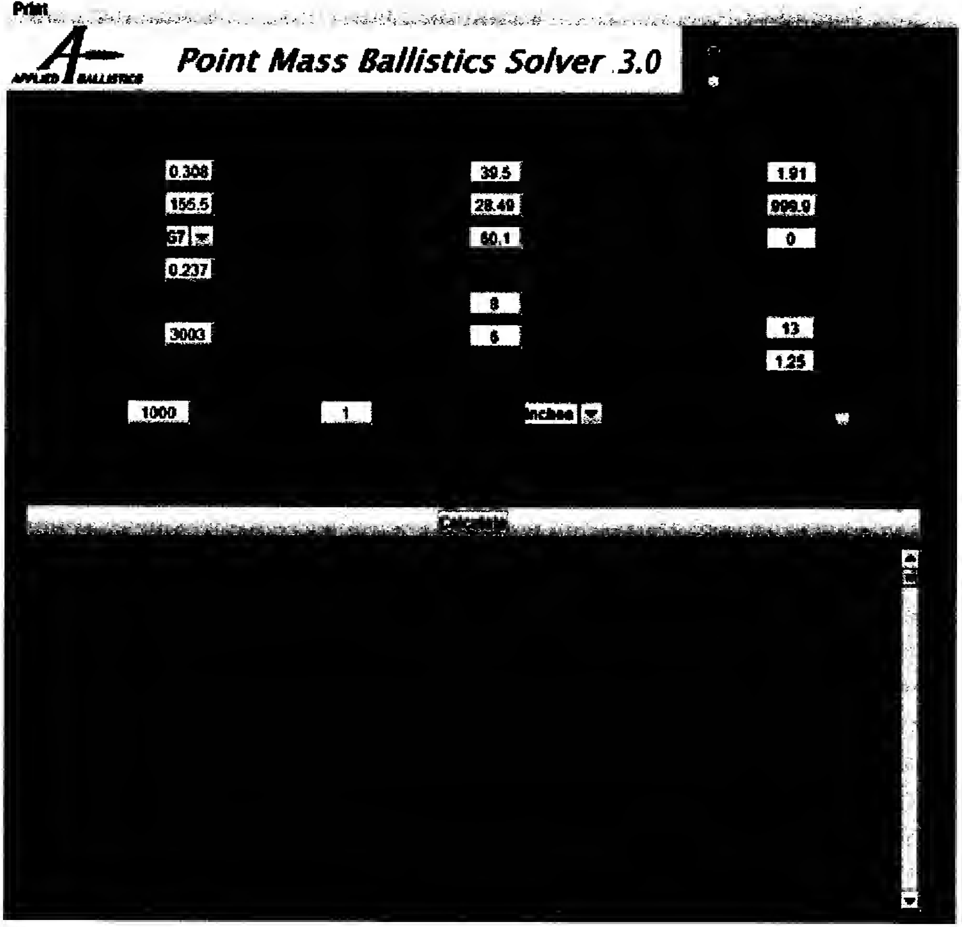

Figure 8.5. Iterate on zero range until the predicted impact point at 187 yards is what was actually observed.

Common ballistics program pitfalls

It's been stated several times that a ballistics program can't be more accurate than its inputs(as computer programmers say: 'GIGO', or Garbage In = Garbage Out). This is common sense, but how do you know how good the inputs are? Which ones are more important, and which ones are OK to fudge? Beyond that, what are the common mistakes made in interpreting the results? Let's start with inputs.

Historically, the BC has been a huge problem for reasons discussed elsewhere in this book. Inconsistent methods of creating BCs by the various bullet companies, and the tradition of referencing all bullets to the antiquated G1 standard have been the biggest problems with getting a truly accurate BCs for use in generating accurate trajectory tables. I've addressed this problem by providing experimentally measured BCs, referenced to the proper G7 standard. Simply look up the bullet you're shooting in *Ballistic Performance of Rifle Bullets*, and use the G7 referenced BC. You won't find more accurate BCs anywhere, not even from the bullet makers' published data.

There's another aspect of BC to consider other than what standard projectile it's referenced to. When bullets are test fired for BC, the result is always corrected for *standard conditions*. There can be a potential problem if you take a BC that's corrected to one standard atmosphere, and use it in a program that assumes a different standard atmosphere. For example, all of the BC's published in *Ballistic Performance of Rifle Bullets* are corrected for ICAO[15] standard sea level conditions, and the included ballistics software works with ICAO so the BC's and the program are *compatible*. If you were to use these ICAO corrected BC's in a ballistics program that uses the older ASM atmosphere model, the resulting trajectory would be in error. Specifically, if you use a BC that's corrected for the ICAO atmosphere in a program that assumes ASM, the program will model the bullet as having a 2% higher BC than it actually has. If you've ever compared ballistics programs and found their output to disagree when given the same inputs, this is one possible explanation. Part of learning to use a ballistics program correctly is to find out what atmosphere model is used, and make sure you give it compatible BC's. Most modern programs and bullet manufacturers use the newer ICAO standard, but it is worth confirming just to be on the safe side.

Next is the muzzle velocity input. It's best to measure the muzzle velocity of your load directly with a chronograph rather than rely on the predictions of reloading manuals. Those manuals are meant to be used as a guideline to get you in the ballpark and keep you away from dangerous loads. Due to the accuracy of the methods used to generate the data, variations between lots of powder and primers, not to mention differences between barrels, you cannot expect a reloading manual to give you a sufficiently accurate prediction of muzzle velocity. Measuring MV with a chronograph is the best way, and if you get the opportunity to test your chronograph against another unit, do it. Hopefully both units will read the same velocity for shots fired thru them both in tandem, in which case you can have more confidence that your chronograph (and the other one) is actually accurate. If you rely on just one unit that's never been verified, you could be using skewed velocities and not know it. Also, the more data you can collect on different days, the better your understanding of your average velocity will be. Chronographs can be sensitive to different light conditions, and might give you bad results on a particular day. Testing over multiple days should reveal the error. Also, testing in various weather conditions, specifically involving significant temperature changes will tell you if the velocities of your loads are sensitive to that variable. You can never know too much about your muzzle velocity! It is a mistake to measure the number once and assume it never changes.

If you're using truly accurate G7 BCs, and well understood muzzle velocity data, you're most of the way to a respectable solution.

Atmospheric conditions can be important, but you usually don't know what they're going to be when you're generating your drop charts at the computer. The best you can do is look up the average conditions for the season at the altitude you'll be shooting at. If you use average conditions for that location, chances are you'll be close to reality. What you don't want to do is ignore the variables just because you don't know exactly what they'll be. The default atmospheric conditions are for sea level, where the air is denser than in most real world conditions. Of course if you have a ballistics program on a PDA that you can take into the field, you can enter the current, measured conditions and get a tailored solution. This is the best way.

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[15] International Civil Aviation Organization

The height of the sights above the bore line (sight height) is a trivial but important number to get right. Most sights will be between 1.5" to 3.5" above the bore. Take the time to measure it and enter the correct value rather than leaving it at the default height if you want your drop tables to be accurate. A simple way to measure the sight height is to measure the diameter of the barrel just ahead of the scope bell with a set of calibers, and divide by 2. Now measure the outside diameter of the scope bell and divide by 2. Now measure the gap between the scope bell and barrel, and add it to the previous two numbers. The sum of these 3 distances is the height of the sight line above the bore line.

Problems with wind usually have less to do with the accuracy of the wind deflection predicted by the program, and more to do with the difficulty of determining the true wind speed and direction in the field. Wind should be the biggest unknown in long range shooting.

The zero range is a simple variable that's often taken for granted. It's common practice to zero rifles in from a solid Benchrest, then take them hunting and shoot from a bi-pod, or some other kind of rest that's different than what the rifle was zeroed from. This difference in shooting platforms can easily make a difference in where a rifle hits. Also, sometimes the sighting in process isn't adequate to know exactly where the true point of impact is. If you shoot and adjust until your last shot hit dead center, it's a good idea to shoot a group of at least 3 to 5 shots to confirm that the average point of impact is truly zeroed, and it's not just based on one shot. This brings up another problem, which is the *wandering zero* that some rifles have as their barrels heat up. The process of manufacturing a rifle barrel can introduce stress into the steel of the barrel, and as the barrel heats up, the stress can cause it to warp slightly, which results in a wandering point of impact. This is part of what makes *cold bore shots* so challenging. It's easy to walk shots into the center of a target, but what happens if it takes the rifle 10 shots to get centered, and you let it cool for an hour. Will the first shot from the cold barrel land where the last one did from a hot barrel? Probably not. *Don't take your rifle's zero for granted!* If you expect to be successful at hitting targets from a cold barrel, you need to know where your rifle will hit with a cold barrel, and not assume it's the same zero that was established after prolonged shooting.

That pretty much covers all the important inputs. If you're careful, and do the best you can to enter accurate input, you can be assured that the program will produce accurate output.

Accurate output doesn't mean you're home free. You still have to interpret and apply the output properly. Mistakes on the application side have to do with understanding your sights, a subject which is covered in the next chapter. Basically, you have to be careful when converting inches of drop into scope clicks. Most scope knobs are graduated in ¼ MOA clicks, where 1 MOA is *approximately* equal to 1" per 100 yards. However, the true definition of 1 MOA is 1.047" at 100 yards. This might not be important at close range, but can cause a 0.47" aiming error at 1000 yards for every 1 MOA of adjustment. In a typical trajectory requiring 30 MOA of elevation to zero at 1000 yards, that's more than 14" of error.

One very common mistake involving ballistics programs has to do specifically with sights. Unfortunately it's very common for shooters to trust that their sight adjustments are precisely as advertised, usually ¼ MOA per click. Shooters will measure their muzzle velocity, range, atmospherics, and record the number of *clicks* it takes to be zeroed at a particular range. The *clicks* are converted to drop according to the *assumption* that each click is precisely worth its advertised value. If this *derived* drop doesn't agree with the output of the ballistics programs, most shooters assume it's because the BC needs to be adjusted (which is sometimes the case). Most of the time, the mismatch results from the fact that the scope clicks are not worth precisely ¼ MOA, but a little more or less. In other words, the inexact scope adjustment creates the *perception* that the bullet drops more or less than it actually does. If the shooter adjusts the BC input so that a ballistics program matches their *perceived* trajectory, then all the other metrics predicted by the program will be wrong (wind deflection, retained velocity, energy, etc). Furthermore, this false BC is useless for someone else (or the same shooter) using a different scope. The details regarding sights are presented in the following chapter, but it's important to be aware of the relationship between the sight/scope, and the *actual bullet drop*.

Using Density Altitude

A ballistics program needs to know atmospherics including temperature, pressure and humidity in order to calculate *air density*. Air density is the most important thing about the atmosphere for the purposes of calculating a ballistic trajectory. Density altitude is a way to shortcut the requirement to enter all three atmospheric parameters. Density altitude can be defined as follows: The altitude in the *standard atmosphere* model that corresponds to the current air density at your location. For example, let's say the atmospherics measured on location are: air temperature 75 degrees F, station pressure 26.80 inHg, and humidity 68%. This combination of atmospheric parameters results in an air density of 0.06595 lb/ft^3. In the standard atmosphere, this precise air density occurs at an altitude of 5000 feet.

Therefore, the density altitude for that set of conditions is 5000 feet. *It doesn't matter what your actual altitude is*, all that's important is what altitude that density occurs at in the standard atmosphere. When you enter 5000 feet density altitude into the computer program, it simply looks up the standard air density for that altitude (0.06595 lb/ft^3), applies that density, and the trajectory never knows the difference. There is one *gotcha* to using the density altitude approach, which I'll explain soon.

Density altitude is very useful if you're dealing with printed trajectory tables. Imagine how many tables would be required to cover every possible combination of temperature, pressure and humidity with a corresponding trajectory table. It's just not feasible. However, if you have tables as a function of density altitude, say for every 1000 feet, that can be a very useful tool. You'll find that any combination of atmospheric conditions results in a density altitude that you have a table for. This, and the fact that it saves two inputs on a ballistics program interface are two very good reasons to use density altitude to calculate trajectories. Of course you need a device that outputs density altitude which is easy to find (Kestrel).

Now there is a slight downside to using density altitude for ballistics calculations. Remember that the speed of sound depends on the temperature of the air. If you're not telling the program what the air temperature is, it has no way to correct the speed of sound for air temperature. This is important because the Mach number of the bullet depends on the speed of sound, and the Mach number is used to look up the drag coefficient. In essence, *if you don't tell the program what the air temperature is, it can't assign the proper drag coefficient*, and the integrity of the solution suffers. Having said that, the effect can be quite minor, even negligible in most cases. For example, if the actual air temperature is close to the standard air temperature (59 degrees F), then there will be no error because the program is already using this standard definition. Also, if the trajectory is fully supersonic, there will be a very small error in the predicted trajectory. If the trajectory slows down to near sonic speed, it can become important if you're at a temperature that's significantly different from the standard air temperature.

Range Yards	**Velocity *true***	**Drop *true***	**Drop *DA***	**Error**
500	1852	58.5"	58.4"	0.1"
1000	1164	388.4"	385.6"	2.8"
1500	932	1348.6"	1342.9"	5.7"

Table 8.4. Not accounting for the temperature effects on speed of sound.

Here's an example to illustrate the potential magnitude of the error. Consider a .308 caliber, 175 grain bullet with a G7 BC of 0.240 lb/in^2 fired a 2700 fps and zeroed at 100 yards. The atmospheric conditions are 29.92 inHg station pressure, 0% humidity, and 79 degrees F (+20 degrees F above *standard*). Under these conditions, the air density is 0.07357 lb/in^3 and the speed of sound is 1137.8 fps. Using these parameters in a ballistics program, the *true* drop is listed in Table 8.4 under Drop *true.* Given these atmospheric conditions, the density altitude is 1320 feet. If you calculated a trajectory based on just that density altitude and the assumed *standard* speed of sound of 1116.5 fps, the predicted drop would be listed under Drop *DA* in Table 8.4. Notice that while the bullet is still comfortably sonic, the error is negligible at 0.1". At the 1000 yard mark, the trajectory is near the middle of transonic flight, and the error in predicted trajectory has grown to 2.8", just about equal to a single 1/4 MOA click. At 1500 yards, when the bullet is well into subsonic flight, the error in the trajectory prediction has grown to 5.7", or about 0.4 MOA.

Of course if a ballistics program were to accept density altitude and temperature inputs, it could fully calculate air density *and* account for the effect of temperature on speed of sound and there would be no error. However in that case, you're inputting 2 variables, when 3 would get you the same full solution.

In conclusion, the use of density altitude for calculating trajectories can be a very useful way to create printed trajectories that cover many combinations of atmospherics and are acceptably accurate for most purposes. It can also be used to shortcut a couple inputs with an computer ballistics program. However, there will be some very small error in the resulting solution when shooting at non-standard temperatures.

Trajectory Validation, or "Truing"

Sometimes a shooter doesn't have access to an accurate chronograph, or is working with a bullet that has an uncertain BC, or has some other uncertainty about the inputs to the ballistics program, but still wants to use the program to predict a trajectory. In the case where inputs are unknown or uncertain, a ballistic solution can be *tweaked* to match some real world data. Some programs have a built in feature to automatically find the BC and/or MV that is required to match your real world drop.

For example, let's say you know your muzzle velocity is 2650 fps, but you don't know the BC for a particular bullet that you're shooting. You can simply take some long range shots at a known distance, note the point of impact, and adjust the BC in the program until the output matches the observed impact. Calibrating a solution like this will result in a prediction that's *better than nothing,* BUT ***it is highly recommended that the shooter make every effort to collect and enter accurate inputs to the ballistic solver.***

In the above example, BC was the only unknown factor. As long as all the other variables are known, in theory the shooter should be able to arrive at the correct BC provided he's testing at a far enough range, and the rifle has the accuracy to resolve drop with a high degree of certainty.

Sometimes shooters don't know their muzzle velocity or the BC but still want to use a ballistics program to get a useful trajectory prediction. This is where a calibration exercise has the potential to be problematic. If you choose the wrong variable to *tweak,* the result can be a solution that's only right for one distance, and has error at all other distances. For example, consider a trajectory based on an *actual* muzzle velocity of 2650 fps and a G7 BC of 0.240; the observed drop will be 92" at 600 yards. Now, if you didn't know the MV or BC, you can find thru trial and error that a MV of 2700 fps and a G7 BC of 0.218 produce a trajectory prediction equal to the observed 92" of drop at 600 yards. Based on this, you would have pretty high confidence in the solution that you *calibrated* based on observation. In fact, there will be very little error in this predicted trajectory over short range. However, the problem comes in when you get far away from the calibration point. For example, at 1000 yards, the true drop of the bullet will be 401", but the *calibrated* drop which is based on the wrong MV and BC would be 420", an error of 19". Figure 8.6 below shows an example of a trajectory that's *corrected* at one range and off at other ranges.

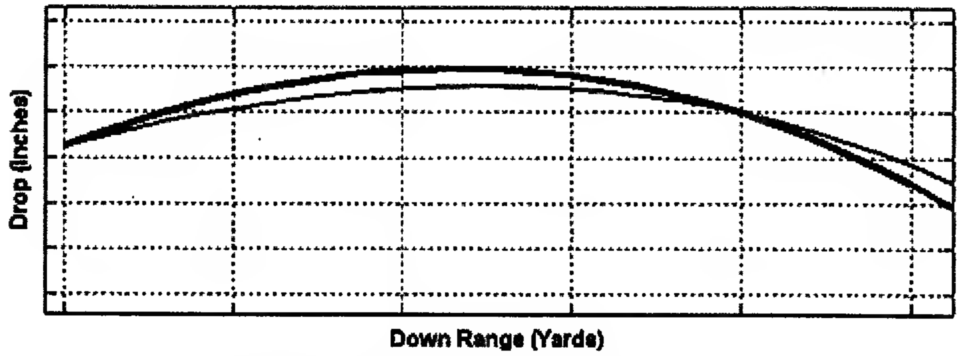


Figure 8.6. Trajectory validation can correct a trajectory for a single point, but may result in more or less error at other ranges.

The above is presented to illustrate the potential problems with trajectory calibration/validation/truing. It is possible to use this method more effectively by gathering the test points at a farther range for example, or locking down all but one of the variables.

In conclusion, the act of *falsifying* inputs to a ballistics program should be avoided if at all possible. If a scenario exists where all the inputs cannot possibly be known with a high degree of certainty (as is commonly the case in some scenarios), then using *conditioned* inputs is the only way to get a trajectory prediction. If you find yourself in a situation where you have to falsify inputs, choose the input with great care and be warned that the trajectory prediction may be inaccurate for ranges far from the distance used to calibrate the solution.

Conclusions

The objective of this chapter was to give the reader the knowledge and confidence to successfully use a ballistics program as a tool for long range shooting. The intent is not to sell you on a particular solution method or program. There are plenty of free programs that are all accurate. The bottom line is that if you use them properly, they do predict accurate trajectories as demonstrated by the experiment described in this chapter.

It would be a mistake to think that mastering the ballistics program is all that's required to be successful at long range shooting. It's certainly an important link in the kill chain, but it's still just one link. There are many links before and after that are just as important for hitting targets at long range.

Chapter 9: Getting Control of Sights

The previous chapters have presented the information that's required to understand and produce very accurate trajectory predictions. However, the most perfectly accurate firing solution won't put you on target if you don't have control of your sights. *Understanding sights is the critical bridge between* ***knowing where your bullet's going,*** *and* ***properly correcting for it.*** Without a complete and accurate understanding of your sights, you will not be able to hit targets at long range, whether you're using a scope or iron/aperture sights. I'm not talking about knowing how the sights are *supposed to move* (as advertised, MOA vs MILS vs inches, etc.) I'm talking about knowing for sure how they *actually move*, as measured.

The importance of understanding sight adjustments can be illustrated with a very typical example that's played out countless times in all disciplines of long range shooting. Let's say a serious shooter diligently measures his muzzle velocity and all the atmospherics for his given location. He's using a very accurate BC (hopefully referenced to the G7 standard), and he's accounted for the sight height and even knows the *cold bore* zero of his rifle. He's got a target at 1000 yards, and the carefully generated, ultra accurate firing solution tells him his bullet will have 314.1" of drop, which is exactly 30 MOA at that range. So he carefully turns his scope knobs up 30 MOA and fires. As he watches his bullet sail 2 feet over the target, he scoffs at the supposed accuracy of his expensive software and PDA and gives up on the possibility of reliable trajectory predictions altogether. The fall of the shot is noted in a log book, and revered as the *true* drop of the bullet at 1000 yards

Figure 9.1. The sight is the critical link that corrects for the bullet's trajectory. Learn the characteristics of your sight well.

for that rifle in those conditions, while the firing solutions of the PDA are from that day on, treated as an unreliable guideline of uncertain accuracy.

The experiment described in the previous chapter demonstrated that when ballistics programs are given truly accurate inputs, they do in fact return truly accurate outputs. So how could our shooter in the above example have possibly missed? He missed because he made a basic, beginner's assumption that his scope's crosshairs move exactly as advertised, ¼ MOA per click, all the way to 30 MOA.

When finding a zero for a rifle at a given range, you can assume that the scope adjustments are about what they say, and keep adjusting them until you're happy with where your shots are landing. It doesn't matter how many clicks it took, you just know that the rifle is now zeroed. However, *if you need to adjust the scope by a precise amount in order to account for gravity drop on a long range shot, it's imperative that you know exactly how much your crosshairs actually move when you turn the knobs.* Simply assuming that each click is what it's advertised to be is a bad policy, and will cause misses at long range. What's worse, this problem can erode a shooter's confidence in his firing solution, and leave him guessing about how much to adjust his sights.

This problem of imperfect sight adjustments has led to many old wives' tales that persist throughout the long range shooting community. For example; consider the belief that a certain bullet will have a significantly different BC (manifested as different amounts of drop) when fired from different rifles. Not true. This is an illusion that's created by the subtle differences in the *actual* sight adjustments of various scopes. If two shooters are shooting the same bullet, properly stabilized, at the same muzzle velocity, with the same sight height, zero range, atmospheric conditions, etc., and one shooter needs to come up 30 MOA from a 100 yard zero to hit center at 1000 yards, and the other guy needs to come up 31 MOA, it's not because the bullet actually flies differently from the two rifles! The difference is that one scope required 30 MOA to correct for the drop, and the other scope required 31 MOA to correct for the *same drop.* The most likely possibility is that the labeled scope adjustments for the two scopes are not the same. However, one could argue that if a rifle doesn't have a fast enough twist barrel to adequately stabilize the bullet, that its BC would suffer and cause the shots to actually hit lower which *is* a real possibility. My example assumes adequate bullet stability from both rifle barrels. If adequate stability exists, the BC of a bullet is very consistent from all rifles. The issue of over *stabilization*, and its supposed effects on BC will be discussed in the next chapter on bullet stability.

The tall target test

The good news is that the problem of uncertain sight adjustments can be fixed with one trip to the range. Here's how to do it:

1. At a measured distance of 100 yards, set up a 4 foot tall target with the aim point near the bottom of the target.

2. Using a plumb bob or level, draw a vertical line extending from the aim point up to the top of the target.
3. Fire a 5 shot group at the aim point with your 100 yard zero.
4. Adjust the scope up 10 MOA and fire another 5 shot group.
5. Adjust the scope up 10 more MOA and fire another 5 shot group.
6. Adjust the scope up 10 more MOA and fire another 5 shot group. At this point, you should be hitting 30 MOA above your aim point.
7. Measure the distance between the centers of the groups and see if they're truly 10 MOA apart (10.47" at 100 yards). If not, you need to establish a correction factor for your sight adjustments.

There's more than one way to characterize the movement of your crosshairs. One way is to figure out how many MOA each click is worth. For example, let's say your first two groups were 11.1" apart. The next step is to figure out how many MOA the crosshairs moved. Since 1 MOA is 1.047" at 100 yards, you can figure that the crosshairs moved 11.1"/1.047 = 10.60 MOA. That means the crosshairs moved 10.60 MOA/40 clicks = 0.265 MOA per click which is more than the advertised 0.25 MOA per click. You may find that a different correction factor is required near the top of the scopes adjustment than at the bottom and middle. These correction factors need to be recorded and applied when large sight adjustments are required in the field.

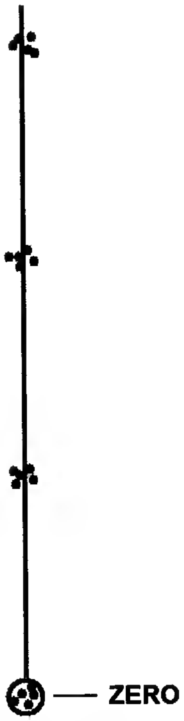


Figure 9.2. The tall target test.

Another way is to forget about MOA all together, and use another unit: Inches Per Hundred Yards (IPHY). Using IPHY makes it easier to go from inches of drop at some range to scope clicks. You don't have to worry about the fact that 1 MOA = 1.047" at 100 yards. Using IPHY, if you have 300.0" of drop at 1000 yards, you need to adjust your scope up 30 IPHY. Figuring out how many IPHY each click is worth is easy using the vertical target test. You know that each group is 40 clicks apart (80 clicks if you have 1/8 MOA clicks). So if the groups are 11.1" apart, you can say that each click is worth 11.1"/40 clicks = 0.2775 IPHY. Now if you have that shot at 1000 yards that requires 300.0" of correction, you can figure out how many clicks are required by dividing 300.0"/(0.2775 IPHY*10 (hundred yards)) = 108 clicks. On your scope turret, this would read as 27 MOA, even though the crosshairs have actually moved 28.65 MOA.

Some shooters calibrate their scope adjustments by revolution. For example, the first scope revolution might move the crosshairs 0.2775 IPHY, but the second revolution moves the crosshairs 0.255 IPHY per click. This is the reason for shooting 4 groups, each 10 MOA apart so that you can see if the scope adjustment is constant for its full range or not. Doing this test at least once is required for calibrating your scope adjustments, but it's a good idea to check it from time to time just to make sure the adjustments are repeatable over the scopes adjustment range. Be sure to measure the actual range you perform the *tall target test.* Don't assume it's actually 100 yards just because the sign says so and you've always assumed it was, measure it!

Another thing you can learn from the *tall target test* is how *level* your sights are. Insuring that your sights are level is another very important part getting control of your sights and hitting targets at long range.

Cant

Cant, or tilt, or roll, is when the crosshairs aren't straight up and down. This causes a problem for long range shooting because when you adjust the scope to account for a lot of bullet drop, you will unintentionally introduce a horizontal error if the sights are canted.

To visualize the effect of cant, imagine a rifle that's got its crosshairs adjusted so the trajectory is zeroed at 1000 yards. This takes a lot of vertical adjustment, we'll say 300" for this example. Now roll that rifle over on its side and shoot at the target 1000 yards away. Where do you think the bullet will go? By rolling the rifle on its side, you've changed the *vertical* adjustment required to account for bullet drop into a *horizontal* adjustment. Furthermore, the scope now has no vertical adjustment to account for drop in this orientation. So the bullet will hit about 300" low and 300" to the side (whichever side the rifle is rolled towards). This is an extreme example, but it illustrates the effect of canting the rifle. It takes a lot of vertical sight adjustment to be zeroed on a target at long range. If the rifle is canted at all, then some of that vertical adjustment *bleeds over* into the horizontal plane, and subtracts from the vertical plane. As an example, if it takes 300" of scope adjustment to be zeroed at 1000 yards and your sights are canted by 1 degree, you will hit over 5" to the side of your aimpoint. Small amounts of cant won't affect vertical impact nearly as much as horizontal impact. The amount of horizontal error from canting is greater as the range increases because more vertical adjustment is required.

The best policy for most long range shooting scenarios is to get the rifle perfectly level so the windage and elevation adjustments are purely independent. However there are some rare occasions (a sniper in an urban hide, for example) where a shooter might be forced to cant a rifle in order to see thru a hole in a wall, or under a door. In this case, there is a rule of thumb that can be used to compensate for the cant. The same rule of thumb can be used to estimate the error that will be induced by inadvertent cant.

Rule of thumb for calculating POI with cant

You can use the following rule of thumb to estimate where your shot will fall when fired from a canted rifle. In order for this rule to work, you have to be using a short range (100 yard/meter) zero for your rifle.

- Determine the elevation required to engage the target at a given range.
- Add 3 MOA, or 1 MIL to the elevation correction you would use to engage the target.
- Multiply this sum by the sin of the cant angle. The result is the horizontal displacement of the shot.
- Multiply the sum by the cosine of the cant angle to approximate your *effective* elevation.

For example, let's say the target is at 600 yards, and you're shooting at a 5 degree cant. It normally takes 13 MOA to be zeroed at 600 yards. Add 3 MOA, that's 16 MOA. Now multiply that by the sin of the cant angle: 16*sin(5) = 1.4 MOA, or 8.8" at 600 yards. That's how far to the side you would hit at 600 yards with a 5 degree cant. Your effective vertical adjustment would be 16*cos(5) = 15.94 MOA. This means your shot will be 0.06 MOA lower than intended, or 0.4" lower.

In the case where the rifle is tilted 90 degrees, you would first turn the elevation down 3 MOA or 1 MIL, then simply use your windage dial as the elevation and vice versa. Note that the rifle is likely to have a fundamental shift in zero when supported on its side compared to being upright. If you plan to shoot in this orientation, you're advised to established a *90 degree zero* for your rifle by firing it on its side and noting the sight settings required to zero, then work the turrets from there (elevation is windage and vice versa).

Eliminating cant

If you're among the 99.9% of normal shooters who don't *need* to cant your sights, then every effort should be made to eliminate cant entirely. The above rule of thumb can easily show you the consequences of a small inadvertent cant. To eliminate cant, you just need a simple sight level.

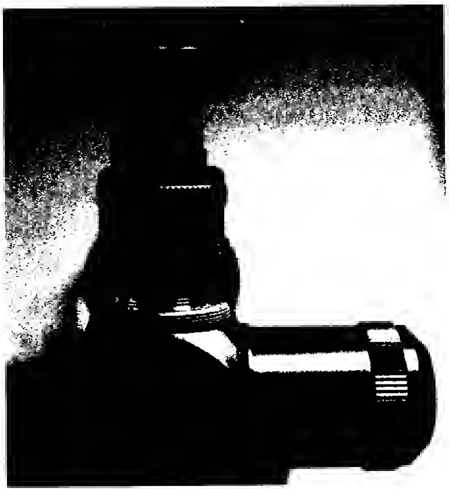


Figure 9.3. View of the vertical adjustment turret and scope level.

Sight levels are made that attach to scopes, scope bases, front aperture sights, or other places of a rifle that can be seen from the shooting position. The level should be installed using a reference line of some kind, preferably a plumb line. The crosshairs of the scope are held fixed in relation to the reference line while the level is installed so it reads level when the vertical crosshair of the scope is aligned with the plumb line. The *tall target test* outlined previously for calibrating adjustments can also be used to confirm that the scope is tracking straight up. Leveling the crosshairs with a plumb line as described will work as long as the crosshairs actually move straight up. In other words, if the vertical crosshair is installed at a slight angle to the mechanism that moves the crosshairs, there will be a tracking problem. The *tall target test* will reveal a tracking problem. Generally, tracking problems like this are not very common, but it's worth checking for when you're calibrating scope adjustment.

It's not actually critical that the scope is mounted level on the rifle. The scope and sight level have to be in sync, but if they're on the rifle at a small rotation angle, it's OK. Some target rifle shooters install their sights with some cant intentionally to make the rifle more comfortable to shoot. As long as the sights are level, the elevation and windage adjustments will track properly and it won't matter that the rifle is canted.

The overall philosophy of dealing with sights is: ***DON'T TAKE ANYTHING FOR GRANTED!*** *Don't take it for granted that the crosshairs move exactly as advertised. Don't take it for granted that the crosshairs are actually level, and track exactly vertical. Don't take it for granted that the range you're shooting the calibration test at is exactly 100 yards without measuring it. The bottom line is to deal in absolute fundamentals, measure them, and remove all the assumptions. If you don't measure everything directly with calipers, tape measures, rangefinders, levels and plumb lines, you can't be sure that your sights are properly calibrated. Don't ever assume that something is what it says without measuring it. This is the key to insuring that the bridge between your predicted bullet path and your intended impact point is solid and reliable. Failing to be meticulous about sights is a huge reason for missing targets at long range.* ***Don't take sights for granted!***

There is one more issue dealing with long range sights that I want to address before getting into some topics specific to iron/aperture sights. The available range of vertical adjustment is an important thing to consider about a scope for long range shooting. It's a common limitation for a beginner to show up at a 1000 yard range for the first time and start turning his scope knobs in an attempt to get zeroed, only to discover that the scope doesn't have enough adjustment. In other words, the scope is adjusted up as far as it can go, and the bullets are still falling short. There are several ways to fix this problem. The most common is a tapered scope base. A tapered scope base can either be one piece or two (2 piece tapered bases have to come in a matched pair). To the naked eye, it looks just like a normal base, but it's actually *ramped*, so that the rear is higher than the front. 20 MOA is a typical angle for a tapered base. What this accomplishes is that it puts your 100 yard zero near the bottom of the scope's adjustment range so that you increase the amount of elevation adjustment that is available. For example, if you have a scope with 50 MOA of total vertical adjustment and you mount it one standard bases, your 100 yard zero will likely be about ½ way up the scope's range of vertical adjustment. You'll have 25 MOA available in either direction, up or down. Most of that 25 MOA down-capability will never be used, leaving you with only 25 MOA available to come up for long range shots. If you need 30 MOA, you can't get it. However, if you install this scope on a 20 MOA tapered rail (ie with a downwards slope equivalent to 20-MOA adjustment on the scope), your 100 yard zero will be about 5 MOA from the bottom of the scope's adjustment range, giving you a total of 45 MOA of available elevation adjustment. 45 MOA will get you from a 100 yard zero to 1000 yards or beyond with most normal rounds.

Another way to achieve this effect is with eccentric scope ring inserts. Burris makes nylon inserts that go between the scope tube and rings, and are graduated in various thicknesses. These inserts don't put any bending torque on the scope because they're secured in the rings like a ball joint. By installing thick inserts in the bottom of the rear ring, and a thin insert under the front ring, you can achieve the same effect as the tapered base.

If you mount the scope at too much of an angle, you may lose the ability to zero it at short range. Some shooters do this intentionally on dedicated long range rifles to insure adequate adjustment is available at the extended ranges the rifles are intended for.

A cheap way to achieve the tapered base effect is to simply shim a normal rear base by placing strips of aluminum or film under it. This is not recommended because it causes the scope rings to be out of alignment with each other which places stress on the scope tube.

Even if you have adequate adjustment without a tapered base or scope ring inserts, you can still benefit from them. Let's say your scope has 70 MOA of total vertical adjustment available, and at 100 yards you're right in the middle at 35 MOA up. You have an additional 35 MOA to go up, and you need 32 MOA to be zeroed at 1000 yards. Even though you technically have the range in your scope to achieve full correction at 1000 yards, you're at the very extent of the scope's available adjustment range. This means you're not looking thru the scope's *optical center* which may compromise the quality of the sight picture. Furthermore, a scope is more likely to have inconsistent adjustments near the limit of its adjustment range. So, even a scope with 70 MOA of elevation adjustment benefits from tapered bases. The tapered bases might compromise the quality of the sight picture slightly at short ranges, but you'll be in a better position at long range where the details are more important.

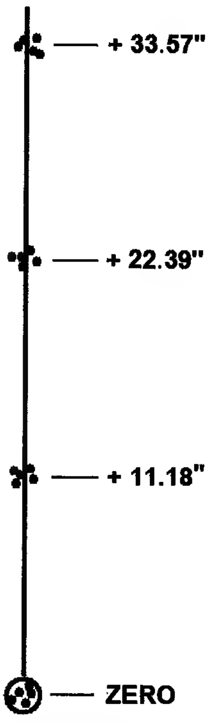
Example 9.1

As an example to illustrate the process of calibrating your sights, we'll consider a shooter who's setting up a rifle for tactical shooting. He's got a good understanding of his bullet's trajectory, but just installed a new scope and wants to get control of the new sight.

Figure 9.4 shows the result of the shooter's *tall target test* as outlined above. Our shooter confirmed the range is in fact 100 yards, and fired 5 shot groups starting at his 100 yard zero and going up 40 clicks between each group while continuing to aim at the original aim point. The 40 clicks between each group caused the actual point of impact to move an average of

11.19”. That means that on average, 1 click is worth 11.19”/40 = 0.280” per 100 yards (IPHY). For completeness, the conversion to MOA is 0.280/1.047 = 0.267 MOA per click.

Notice that all 3 of the 40 click intervals produced almost the same amount of shift in the point of impact. The first and last intervals were both 11.18”, while the middle interval was 11.21”. These are so close that it wouldn’t be worth establishing a separate calibration factor for the middle interval. If the test were repeated, the values for each interval may be slightly different, but the average would still probably be very close to 11.19” per 40 clicks. Notice also that the groups formed right on the plumb line above the original point of aim, which means that the shooter is properly using a sight level, and has the cant under control. As more elevation is applied to adjust the impact further up on the target, the more sensitive the grouping becomes to *rifle cant.* A small amount of rifle cant can go unnoticed with the 100 yard zero. However if there’s a lot of elevation applied to the sight, any small amount of cant will string the group horizontally. In other words, for long range shots that require a lot of elevation, it’s much more important to pay attention to the sight level than when shooting targets at short range.



1st 40 clicks	11.18”
2nd 40 clicks	11.21”
3rd 40 clicks	11.18”
Average	11.19”
IPHY per click:	0.280”

Figure 9.4. The tall target test.

Now that the calibration factor for the scope’s adjustment is known, our tactical shooter can take to the field with confidence, knowing that each click of his scope will move the crosshairs precisely 0.280 Inches Per Hundred Yards (IPHY).

When faced with a real life scenario at 550 yards where the shooter needs to account for 44” of drop, the proper sight adjustment of 44/(0.280*5.5) = 29 clicks (7.25 MOA reading on the scope turret) can be confidently dialed in and the shot taken. Without calibrating the scope, if the shooter just assumed that each click was truly ¼ MOA as advertised, he would have dialed 7.75 MOA on the scope turret to account for the 44” of drop, which would cause the bullet to strike over 2” above the aim point at 550 yards. That error might make a difference, or it might not. Bottom line is that the error, however small, can be avoided if you truly have control of your sights.

Aperture sights

Aperture sights are used in most NRA target shooting disciplines, and almost never for hunting or tactical applications. The size of the sight aperture can be chosen relative to the aiming black of the target and give a very precise sight picture of a *circle-in-a-circle* on paper targets, but trying to center a brown deer in a brown field at long range would not be easy with aperture sights. Much of the discussion about using aperture sights has to do with improving the quality of the sight picture thru various combinations of lenses and color filters, etc. This text will not go into these details of sight picture improvement. Instead, I'll remain focused on getting control of the sights by making accurate adjustments that result in centered shots at all ranges.

The principles of aperture sight operation are the same as for scopes; installing a level to avoid cant, calibrating clicks to their true value, making sure you have enough range of adjustment, and *not taking anything for granted.* There are a few unique things you can do with aperture sights that scopes don't allow.

In order to know exactly how much a click of adjustment is worth on a scope, you have to actually shoot groups and adjust the scope as described above. However, aperture sights have their adjustment mechanism exposed, which means you can measure the movement of the actual sight carriage, and determine the change in aimpoint directly, without having to actually shoot the rifle. Consider a standard rear aperture sight as shown in Figure 9.5. The pitch of the threads and the amount the knob revolves per click will determine how much the aperture actually moves per click. The movement of the aperture, combined with the length of the sight radius, will determine how much the point of aim is actually moved on the target. *It's impossible to know exactly how much 1 click will move the point of aim without also knowing the sight radius.* Rear sights are typically marked as having ¼ or ½ MOA clicks, but the truth is that the true value of a click depends on how the rifle is configured. In order to figure out the exact value of 1 click for an aperture sight, you're going to have to do some trigonometry. Just kidding, I've boiled the math down into a simple relation shown in Equation 9.1.

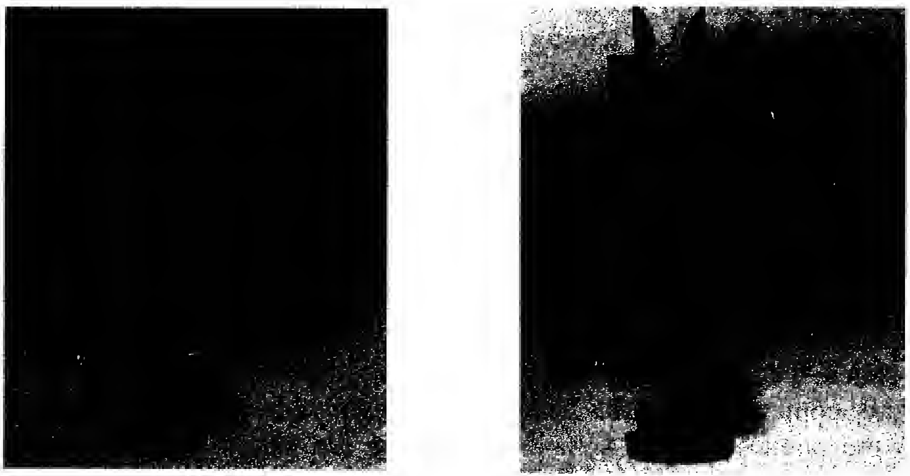
$$1\ click = 171.89\frac{Sight\ movement\ for\ 20\ clicks(inches)}{Sight\ radius(inches)}MOA$$

Equation 9.1

Here's the easy way to figure out how much a click is actually worth on your aperture sight. All you need is your rifle with sights installed, calipers, tape measure, and Equation 9.1.

1. With the sight set to zero, measure from the sight carriage (the part that moves) to the outer edge or frame of the sight as shown in Figure 9.5 (for different models of sights, this measurement can be anything that allows you to determine the movement of the carriage).

2. Turn the sight 20 clicks and measure the distance again as in the right side of Figure 9.5.
3. Subtract the two numbers. This difference is how much the sight actually moves for 20 clicks, measured in inches.
4. With the front and rear sights mounted on the rifle, measure the sight radius. This is the distance from the rear aperture ('peep') to the front aperture. This can be measured with a common tape measure.
5. Once you have measured the movement of the sight over 20 clicks, and the sight radius, use Equation 9.1 to find out how many MOA each click is worth.



Windage on zero, starting point is 0.921"

After 20 clicks, the measurement is 0.796"

Figure 9.5. 20 clicks moved the sight 0.921" – 0.796" = 0.125"

Example 9.2

Consider the rear sight in Figure 9.5. This particular sight has claimed ½ MOA windage clicks for some assumed sight radius. I want to know how much each click is worth on my rifle that has a 35" sight radius. Simply plug the measured sight movement for 20 clicks and the sight radius into Equation 9.1 to determine how many MOA one click is actually worth:

$$1\ click = 171.89 \frac{Sight\ movement\ for\ 20\ clicks\ (inches)}{Sight\ radius\ (inches)}\ MOA$$

$$1\ click = 171.89 \frac{0.125"}{35"} MOA$$

$$1\ click = 0.614\ MOA$$

Meaning 0.614 MOA per click, not the advertised ½ MOA per click.

If you want to know how many Inches Per Hundred Yards (IPHY) the one click is worth, simply multiply the MOA value by 1.047. In the above example, this would result in 1 click = 0.614 * 1.047 = 0.634 inches per hundred yards.

This example was done for the windage knob. You have to repeat the procedure on the elevation travel in order to know the value of each elevation click.

It's important for target shooters to understand the value of their sight adjustments for several reasons. First of all, when you calculate drop at long range, you need to know how many clicks to *come up* in order to correct for the drop at that range. Simply assuming that the value of the sight clicks are ¼ MOA is poor policy, considering the actual value of a sight adjustment depends on the sight radius of the particular rifle it's mounted on. This effect is especially important for shooters who are using a sight extension tube that adds an additional 6"-10" to the sight radius. Using the procedure outlined above, you can quickly and easily determine what your elevation settings need to be with and without the sight extension.

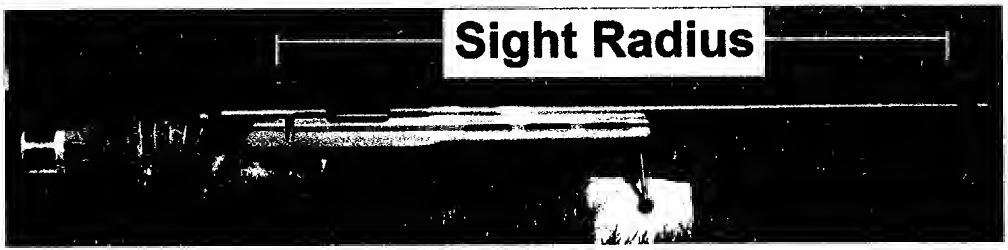


Figure 9.6. The sight radius is measured between apertures.

Another less obvious reason for understanding the true value of your sight adjustment has to do with windage and team shooting. In team shooting events, the wind coaches have to translate their assessment of the wind into accurate sight adjustments for the shooter. Typically, one coach will call wind for all the shooters on the team, each shooter having their own unique rifle with unique sights and sight radius. The best policy for serious team competition is to standardize equipment so that 1 click means the same thing for everyone and the coach doesn't have to account for the subtle differences in equipment from one shooter to the next. Short of standardizing equipment, shooters and coaches should at least understand their relative sight adjustments so that mistakes aren't made when changing shooters. For example, if the first shooter comes off the line with an *indicated* 4 MOA of right windage on his sights, and the second shooter comes up with a different type of sight and a different sight radius, the coach might have him start with 4 MOA. What if the first shooters sights actually only had 3.5 MOA, and the second shooters sights actually move 4.5 MOA when they both *read* 4 MOA? This kind of situation can make life hard on coaches and hurt the overall performance of the team.

This last example will demonstrate how to go all the way from the output of a ballistics program into an accurate aperture sight adjustment.

Example 9.3

Let's say you just got a new Palma rifle, your first ever. You've worked up a good load at the local 100 yard range, and will soon be traveling to your first Palma match in which you'll be shooting at distances of 800, 900, and 1000 yards. How do you figure out what elevation your sight settings should be for the various yard lines?

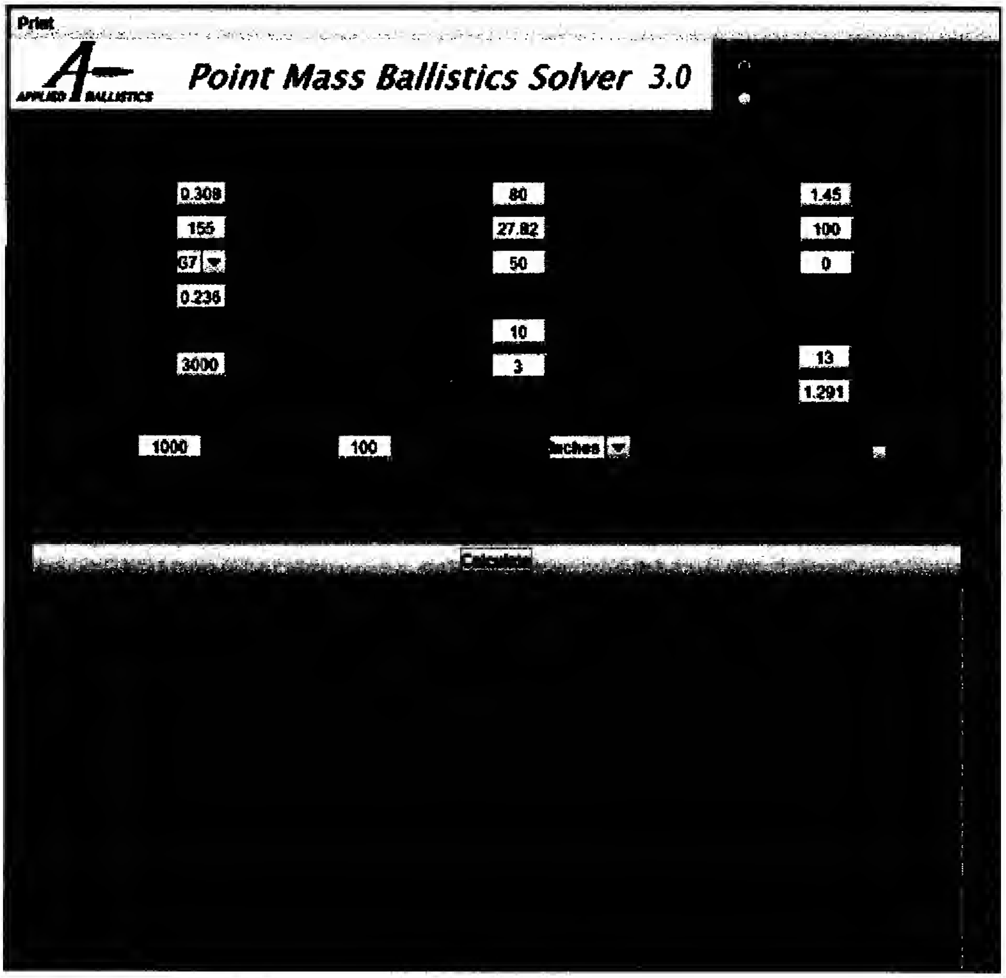


Figure 9.7 Output from the ballistics program.

Well, **you have a 100 yard zero** for your rifle and measured that your **sight height is 1.45"** above the bore center-line. You know the **average muzzle velocity of your bullets is 3000 fps**. You're using Lapua 155 grain Scenars as your bullet of choice. This bullet has a **G7 BC of 0.236 lb/in^2**. The weather for the match is forecasted as **80 degrees** and sunny for the location of the match, which is at **2000 ft above sea level**.

Using Table 8.1, you can find that the standard barometric pressure for an elevation of 2000 feet is **27.82 inHg**. With all of the above information, you can use the included ballistics program to figure out how much the bullet will drop from a 100 yard zero at: 800, 900, and 1000 yards.

Rounding to the nearest inch, the bullet drop at 800, 900 and 1000 yards is -156", -214", and -287".Now you know your trajectory. The next step is to get control of the sights. Measure the sight movement and sight radius to determine how many clicks are required to correct for the drop at each range. Let's say you've measured the elevation travel of your rear sight for 20 clicks and found it to be 0.041". Now you measure the sight radius at 35.5". Applying Equation9.1 tells you that each click is worth: 171.89*0.041"/35.5" = **0.199 MOA**. One more conversion tells you that each click is worth 0.199*1.047 = **0.208 Inches Per Hundred Yards (in/100 yards)**. Table 9.1 shows how to complete the calculations and get the sight adjustments required for 800, 900, and 1000 yards.

If you had assumed that each click of the sights was really ¼ MOA as it's marked, you would go to the match thinking that your zeros for 800, 900, and 1000 yards should be 18.5 MOA, 22.5 MOA, and 27.25 MOA. Your first shot at 800 yards would have been about 40" low in the berm, sending dirt and debris into the pits all over your target puller which won't cost you any points on the sighter shot, but is certainly not a good first impression. If you recognized the problem right away, you might be able to figure out how to hit paper at 900 and 1000 yards with your first shot. Bottom line is that you would be in a bad place if you assumed your sight adjustments were truly ¼ MOA per click. *Don't take anything for granted, measure it!*

Range	**Determine click value at range**	**Bullet drop**	**Clicks required**	**Sight Reading**
800 yards	0.208*8 = 1.664 in per click	156"	156/1.664 = 94	94/4=23.5 MOA
900 yards	0.208*9 = 1.872 in per click	214"	214/1.872 = 114	114/4=28.5 MOA
1000 yards	0.208*10 = 2.080 in per click	287"	287/2.080 = 138	138/4=34.5 MOA

Table 9.1. Determining sight settings for Palma course.

Situations like this are what cause many people to give up on ballistics programs, and have to rely on the collective experience of others. Don't get me wrong, there's nothing wrong with learning from others, but don't think you need some kind of black magic voodoo or owl feathers that's been passed down for generations in order to shoot long range. The fundamentals required to hit targets at long range are well understood and established laws of science that any shooter is empowered to apply for themselves.

Conclusion

The essential hardware required for long range sights is some kind of sight level (to avoid cant), and a tapered base for scopes (to ensure adequate range of vertical adjustment). The essential philosophy of getting control of sights is to measure everything so that you know how much your sights actually move per click, and don't assume they move as advertised. And don't ignore the level.

Chapter 10: Bullet Stability

Bullet stability is a very interesting and mysterious subject for many long range shooters. The term *stability* gets thrown around a lot, mostly as a blanket explanation for some observed behavior that simply can't be explained by anything else. This chapter will take on a *myth-buster* tone at times because there are a lot of false beliefs about stability, its origins and effects.

The history of spin stabilized projectiles is very interesting. If this were a more inclusive text, it would discuss historical facts about how the enhanced accuracy and ballistic performance of spin stabilized projectiles revolutionized the strategies and tactics of past conflicts, especially the American Civil War. Interesting as these events are, this is not a history book, and we will stay focused on the technical understanding of stability.

First, it's a good idea to define what is meant by stability. *Stability is the ability of a projectile to maintain its point forward orientation in flight, and return to that orientation if disturbed.* There are two basic ways to achieve stability for projectiles: fin and spin stability.

Fin stability is how projectiles like darts, arrows and rockets are able to maintain their point forward flight. Fin stability works by forcing the center of aerodynamic pressure behind the projectile's center of mass (via the fins) thus making the projectile *statically stable.* In this configuration, if the projectile's orientation becomes disturbed, an aerodynamic torque effectively applied at the center of pressure (near the fins) will restore the projectile to a point forward orientation, much like a *weathervane* effect. Fin stability is easier to visualize and understand than spin stability because it's so common and familiar. I've explained fin stability only as a backdrop to a discussion about spin stability, on which the remainder of this chapter will focus.

Since bullets don't have fins, their center of pressure is located in front of their center of mass. This is the definition of a *statically unstable* configuration. *In order to maintain point forward flight for a bullet that's* *statically unstable, the bullet requires adequate spin to achieve gyroscopic stability.*

There are actually two components involved in spin stability: gyroscopic stability and dynamic stability. Gyroscopic stability will be investigated first.

Gyroscopically Stabilized Projectiles

Most discussions about bullet stability are restricted to the gyroscopic variety. Gyroscopic stability is affected directly by the twist rate of our barrel, the velocity of the bullet, and the air density that the bullet is launched into. Gyroscopic stability is absolutely necessary for the bullet to fly point forward. Gyroscopic stability works as follows. The spinning mass of the bullet generates a gyroscopic effect which makes the bullet's axis rigid, and resistant to overturning torque. The *rigid axis* effect is what allows a spinning top to remain upright, and allows a gyroscope to maintain its orientation. If the bullet were launched without being spun, the aerodynamic force applied at the center of pressure (on the nose) would generate an overturning torque that would overturn the bullet, and it would tumble for lack of *gyroscopic stability.* If the bullet is spinning fast enough, its axis will be rigid enough to resist the aerodynamic torque on its nose that's trying to cause it to tumble. If the spin is fast enough, the bullet is said to have adequate gyroscopic stability. If the spin is not fast enough, the bullet will lose its orientation and tumble. The gyroscopic stability factor (SG) is the measure of gyroscopic stability applied to the bullet by spin. You can think of SG as the ratio of:

$$Sg = \frac{Rigidity\ of\ the\ spinning\ mass}{Overturning\ aerodynamic\ torque}$$

If the *Rigidity of the spinning mass* is greater than the *Overturning aerodynamic torque*, then SG will be greater than 1.0, and the bullet will be gyroscopically stable. However, if the *Overturning aerodynamic torque* is stronger than the *Rigidity of the spinning mass*, then SG will be less than 1.0 and the bullet will not be stable.

The terms I use in this chapter have been chosen to communicate a basic understanding of stability, and as such would not be 100% precise or inclusive in any technical discussion of the aerodynamic principles involved here. There are other texts that go into the physics and provide complete mathematical descriptions for those who are interested. References are listed at the end of the book, and the Miller twist rule is presented in the Appendix for those who want to investigate the numeric calculation of stability in greater depth. My intent here is to explain the idea of stability in layman's terms. I think the reason for much of the confusion about bullet stability is that it's rarely explained in layman's terms, only in detailed mathematical rigor, which leaves the non-mathematicians scratching their heads and making up their own theories.

Getting back to the gyroscopic stability factor, SG…The major factors that affect the *rigidity of the spinning mass* are:

1. Bullet shape and mass. The shorter, fatter and massive the bullet is, the more *rigidity* it will have at a given rate of spin.
2. Spin rate. Regardless of shape, the faster it is spinning, the more rigid its axis will be. The initial spin rate of the bullet is a product of barrel twist rate and muzzle velocity.

The major factors that affect the *Overturning aerodynamic torque* are:

1. Bullet shape, in particular the ogive (nose). A blunt ogive will push the center of pressure (cp) farther forward, while a long, sharply pointed ogive moves it back. The farther forward the cp is, the more statically unstable the bullet is, and the stronger the overturning torque will be.
2. Velocity. The faster the bullet is traveling, the greater the *aerodynamic force* and accompanying *torque* applied around the center of gravity.
3. Air density. The greater the air density the bullet flies thru, the stronger the *aerodynamic overturning torque* will be because as with bullet velocity, more dense air provides greater resistance to the bullets passage than less dense air.

Notice that *velocity* is a factor in both the *Rigidity of the spinning mass* and the *overturning aerodynamic torque.* This is where we attack the first myth about bullet stability. It is commonly believed that you can *greatly* increase the stability of a bullet by increasing its muzzle velocity because higher muzzle velocity means higher RPM from a given barrel. It's true that the bullet spins faster when launched at higher speeds and has a more rigid axis, *but that's only half the story.* In this case, velocity is a double edged sword. **Velocity also increases the *force applied* to the nose of the bullet at the cp, and strengthens the *overturning aerodynamic torque* which actually makes the bullet *less* stable.** As it turns out, the effect that increased velocity has on the *rigidity of the spinning mass* is slightly greater than the effect of strengthening the *overturning aerodynamic torque*, so the result is a *slight* increase in stability from the higher velocity, but not nearly as much as commonly thought, far less than a 1:1 correlation. For example, increasing the muzzle velocity of a typical .30 caliber 155 grain bullet by 10% from 3000 fps to 3300 fps increases the bullet's RPM by 10%, but only increases SG by 3%. So it's true that velocity affects stability, but due to the offsetting factors, the resulting net effect is quite weak.

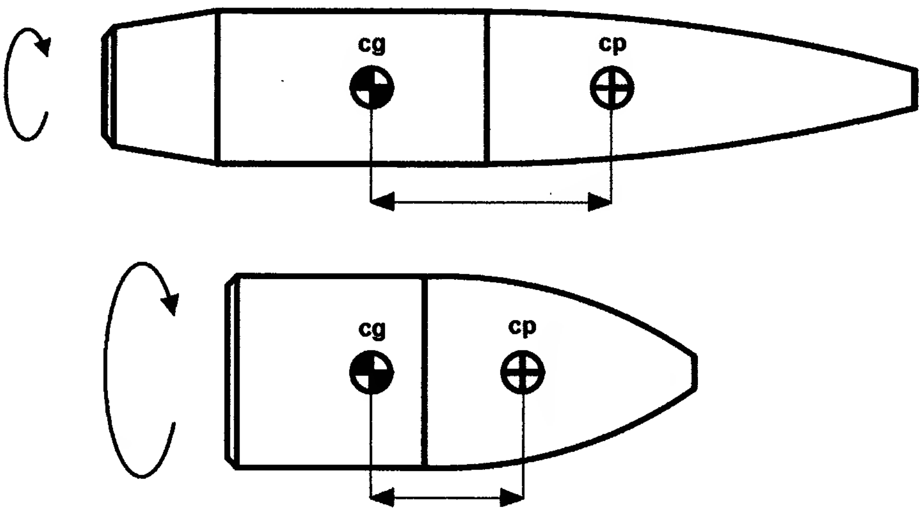


Figure 10.1. The long skinny bullet is harder to stabilize for two reasons. First, there's a greater distance between its center of gravity (cg) and the center of pressure (cp). This makes the bullet more *tipsy*. Secondly, a long skinny bullet has a *less rigid* axis for a given spin rate compared to a short fat bullet.

Velocity also comes into play as the bullet flies downrange. As the bullet flies downrange, *its forward velocity declines much faster than its losing rotational velocity*. This means that the *aerodynamic overturning* torque diminishes at a faster rate than the *rigidity of the spinning mass,* so the gyroscopic stability of the bullet actually increases over its flight. Over a long-range trajectory, a bullet that was launched with an SG of 1.5 at the muzzle can have its SG grow to 4.0 or 5.0 or more by the time it reaches the target. In other words, at the muzzle is where SG will be at a minimum, and it grows as the bullet flies downrange.

The included ballistics program has the ability to calculate the SG (at the muzzle) for a bullet given its caliber, weight, length, barrel twist rate, muzzle velocity and atmospheric conditions. The program runs the Miller twist formula to generate this prediction.

Typically, it's wise to aim for an SG of at least 1.5 when selecting a barrel twist for a particular bullet. Technically speaking, SG only has to be greater than 1.0, so why aim for a higher value? There are a couple of reasons. The more important reason is to have that extra 0.5 of SG as a safety margin. If you aim for an SG of 1.0, and conditions exist that cause it to drop to 0.99, you have a problem. It would be like designing a bridge to hold only up to its max expected weight, but would crumble if one more pound is applied. The 0.5 safety margin in SG is there to account for non-standard atmospheric conditions, imperfectly balanced bullets, and errors in the prediction of the SG value itself. The Miller formula used to predict SG is accurate, but it's not 100% accurate for all bullets. There could be up to +/- 10% or more error in the prediction of SG. In this way, the SG formula and spin drift formula from Chapter 6 have a lot in common. They're both boiled down representations of things that are too complex to calculate directly, and so they have some unavoidable error. In this regard, they are different than the equations of motion in the ballistic program solver which are much more exact, and *can* accurately calculate trajectories if given accurate inputs.

Another reason you want to aim for an SG of 1.5 or higher is to be sure you're maximizing the BC of the bullet. A bullet can fly accurately, group precisely, and otherwise appear to be perfectly stabilized while flying with an SG below 1.5. However, bullets flying with SG's lower than 1.5 can have measurably depressed BC's. Experiments demonstrating the relationship between stability and drag have been published in *Modern Advancements in Long Range Shooting – Volume 1* **[REF 10]**.

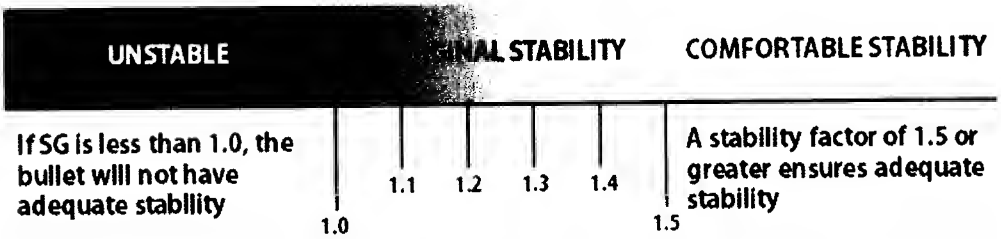

UNSTABLE
NAL STABILITY
COMFORTABLE STABILITY
If SG is less than 1.0, the bullet will not have adequate stability
1.0
1.1
1.2
1.3
1.4
1.5
A stability factor of 1.5 or greater ensures adequate stability

Figure 10.2. It is advisable to stay above the *gray area* of stability, meaning, keep SG above 1.5.

The safety margin of 0.5 that's recommended for SG is not written in stone. The value of this safety margin has been suggested anywhere between 0.3 and 0.5. The military uses a safety margin of 0.5 to 1.0 because of the extreme environments and battle field conditions that its weapons have to operate in. Furthermore, the military designs their weapons to work with a broad range of ammunition types.

Precision BR shooters who are careful and precise and shooting high quality components can get away with a slightly smaller safety margin like 0.1 or 0.2. I recommend an SG of 1.5 for general use and to maximize BC. Figure 10.2 illustrates the *gray area* of gyroscopic stability. Sometimes you can have acceptable performance if the gyroscopic stability is predicted to be in the gray area, but it's advisable to stay above it especially for long range shooting where ballistic performance is important.

Also understand that there is no hard line between where a bullet will be completely stable, vs out of control. There is quite a large grey area where the bullet has marginal stability, somewhere between an SG of 1.0 to 1.1. Consider a bullet launched with marginal stability (lower than recommended twist). This bullet will fly with some amount of pitching and yawing until SG improves enough (thru loss of velocity) to restore point-forward flight. This phenomenon is often described as the bullet *going to sleep* (if the twist is *too* slow, the bullet will simply tumble instead of going to sleep).

This is where I need to be clear about how launch dynamics and stability are related to bullet performance. All bullets are launched with some amount of pitching/yawing motion, however slight. If the bullet has adequate stability (as it will in most cases), it will quickly dampen out these minor disturbances and fly point forward *with no practical consequence to the bullets flight performance (BC).* I'm making a point to be clear on this because many shooters believe that every rifle will put a bullet to sleep differently, and it's one of the reasons given for why bullets (supposedly) fly differently from different rifles. What I'm saying is that *as long as the bullet has adequate stability (SG equal to or greater than 1.5), then the way in which the bullet goes to sleep does not affect its flight performance (BC).*

The following is a case study of measured drag to demonstrate the effect of marginal gyroscopic stability on drag and BC.

The Berger 6mm 95 grain VLD was tested on two occasions in two different barrels. The first test was with a 1:10" twist barrel. The test conditions affecting stability are shown in Figure 10.3. From a 1:10" twist barrel, an SG of 1.07 was predicted for the conditions of this test, which is lower than recommended. Figure 10.3 shows the measured G1 and G7 BC for this bullet fired from both a 1:10" and 1:8" twist barrels. Notice that the measured BC is greater for the faster twist barrel. The reason the bullet has greater drag from the 1:10" twist barrel is because of the *marginal gyroscopic stability* that is imparted by the 1:10" twist barrel. The bullet isn't so unstable that it tumbles; rather it flies with some amount of pitching and yawing motion which increases drag and reduces its *effective BC.*

When the bullet is fired with inadequate stability, the measured drag actually matches the G1 curve better than the G7 curve. The reason is because the bullet starts out with so much extra drag at high speed caused by excessive pitching and yawing. As the bullet flies downrange, becomes more stable, and dampens out its oscillations - ie, as the bullet *goes to sleep* - the drag drops to more normal levels since the bullets flying point forward.

Because the bullet is adequately stabilized from the faster 1:8" twist barrel, the drag is as low as it can be right out of the muzzle because the bullet is flying perfectly point forward. Its drag curve, hence BC, now match the G7 norm as expected.

When fired from a 1:9" twist barrel, this bullet will fly with an SG of 1.32 in standard atmospheric conditions. Don't draw the false conclusion from Figure 10.3 that a 1:9" twist barrel will result in drag that's halfway between that of the 1:8" and 1:10" twist. In fact, the 1:9" twist will produce adequate stability, resulting in the same minimum drag flight as that achieved by the 1:8" twist barrel. Only when the gyroscopic stability falls below 1.5 will the drag begin to rise. In other words, once a bullet is *adequately stable* meaning an SG of 1.5+, the BC is affected very little by making it *more stable*[16].

The 6mm 95 grain VLD was used in this example because its stability requirements have been a source of contention among some shooters who live at different elevations. Since stability is affected by air density, and air density is related to (among other things) altitude above sea level, it's not surprising that shooters who live and shoot at different altitudes will observe different stability characteristics for a given bullet. The 95 grain VLD is marginally stable from a 1:10" twist near sea level but at 5,000 feet above sea level the air density is about 20% less. As a result, any bullet will be 20% more stable at that altitude than at sea level. It's easy to see how arguments can develop about a bullet's stability requirements if the effects of altitude and air density are not understood.

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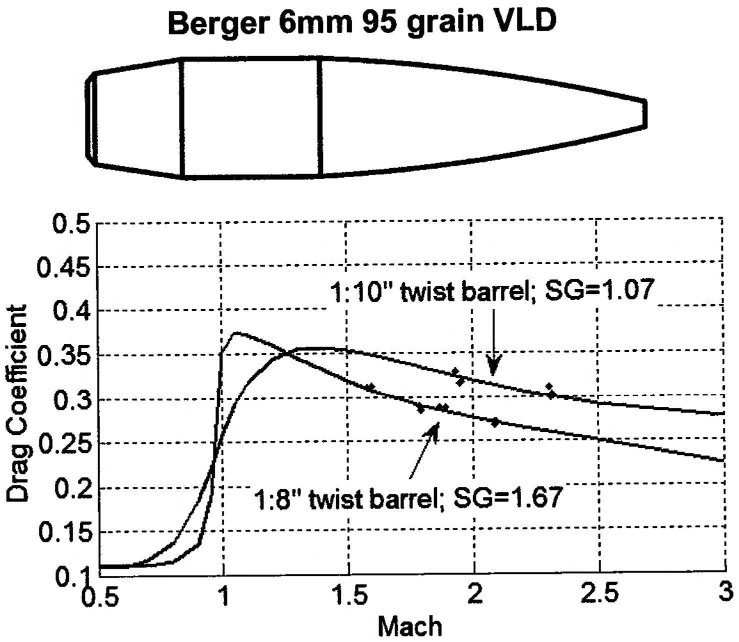
[16] This is true for supersonic flight. Drag thru transonic can be noticeably affected by elevated twist rate and *super-stability* as demonstrated in testing published in *Modern Advancements in Long Range Shooting – Volume 1.*

As already noted, an under-stabilized bullet will suffer more drop and wind deflection than if it were properly stabilized, although groups (precision) may not be noticeably affected.



	Berger 6mm 95 grain VLD	
	1:10 twist	1:8 twist
Muzzle Velocity	2815 fps	2850 fps
Air Temperature	52.7°F	52.7°F
Air Pressure	29.53 inHg	29.77 inHg
Humidity	69.5%	42.1%
Gyroscopic Stability	1.07	1.67
G1 BC	0.416 lb/in^2	0.486 lb/in^2
G7 BC	0.218 lb/in^2	0.249 lb/in^2

Figure 10.3. When fired from the 1:10" twist barrel, the bullet lacks adequate stability and exhibits higher drag from the pitching and yawing motion. When fired from the 1:8" twist barrel, the bullet flies point forward and has much less drag.

It's important to understand that the problem of marginal gyroscopic stability can and should be avoided. There are certain bullets that are very long and heavy for their caliber which require a very fast twist rates in order to be properly stabilized. However, if you go by the recommended twist given by the bullet maker, the bullet will have adequate stability, emerge from the barrel with near zero pitching and yawing motion, and *go to sleep* quickly without affecting performance. The drag increase suffered by the 6mm 95 grain VLD from a 1:10" twist barrel is an example of something bad that can happen if you don't follow the recommended twist requirements provided by the manufacturer.

It's easy to see how the belief that: *bullets fly differently from every rifle* was established. If two shooters were shooting this bullet side by side, one with a 1:10" twist barrel, and the other from a 1:8" twist barrel, they would certainly observe different amounts of drop and wind deflection at long range. It might seem reasonable to extrapolate, and conclude that all bullets fly differently from all guns. In fact, bullets only fly differently from guns that don't properly stabilize them to begin with. As long as the bullet is properly stabilized, it will fly a consistent and predictable trajectory thru the supersonic range of the bullets flight.

Another way that stability is believed to affect bullet flight is the idea of *over stabilization.* The theory goes:

> *"A bullet that is spun excessively fast will not trace with the flight path. As a result, when the bullet drops on the downrange leg of the trajectory, it will retain a nose high orientation, which presents more surface area to the oncoming air flow, and causes increased drag, thereby reducing the effective BC."*

Although there is some truth to this statement, the increase in drag is commonly believed to be much greater than it actually is. It's true that higher stability levels do produce a more rigid spin axis that tends to resist bending as the bullet follows its curved trajectory. However, even bullets with very high stability factors will still trace (sometimes called *track*) very well with the trajectory, the angle will only lag a little more than a slower spinning bullet. An exception to this statement is for very high angles of fire, near 90 degrees, where the bullet would have to turn its axis abruptly at the apex of the trajectory. *Failing to trace* is a consideration for artillery shells fired at high angles because if the round doesn't trace, it won't hit the ground point first which is required to activate the fuse and detonate the charge. Bear in mind that even for such high angles of fire, failure to trace is still uncommon. For the small angles of even the longest range small arms trajectories, it is very easy for the axis of the bullet to trace with the trajectory. To illustrate the difference in drag between a bullet with moderate stability vs very high stability, the 6 Degree Of Freedom (6 DOF) simulation is called on. But first, consider it from a common sense perspective.

The initial elevation angle typically required to zero a trajectory at 1000 yards is about 30 MOA, which is ½ of one degree. On the downrange leg of its trajectory, the bullet will be falling at a slightly steeper angle, maybe ¾ of one degree. Now, if a bullet completely failed to trace, and arrived at the target with its nose in the same orientation it was launched at, it's still only flying with a 1.25 degree nose high angle to its flight path. How much extra drag do you think is induced by flying at a 1.25 degree angle over the second half of the trajectory? Now remember that even a bullet with a very high stability factor *still traces with the flight path*, it just lags a little more than a bullet with a less rigid axis. The 6 DOF simulation will demonstrate the flight dynamics and difference in drag for one bullet at different initial spin rates.

The Berger 7mm 180 grain VLD was chosen as the bullet to model for the 6 DOF simulation because it's so long, and would magnify any additional drag caused by flying at an angle to its trajectory.

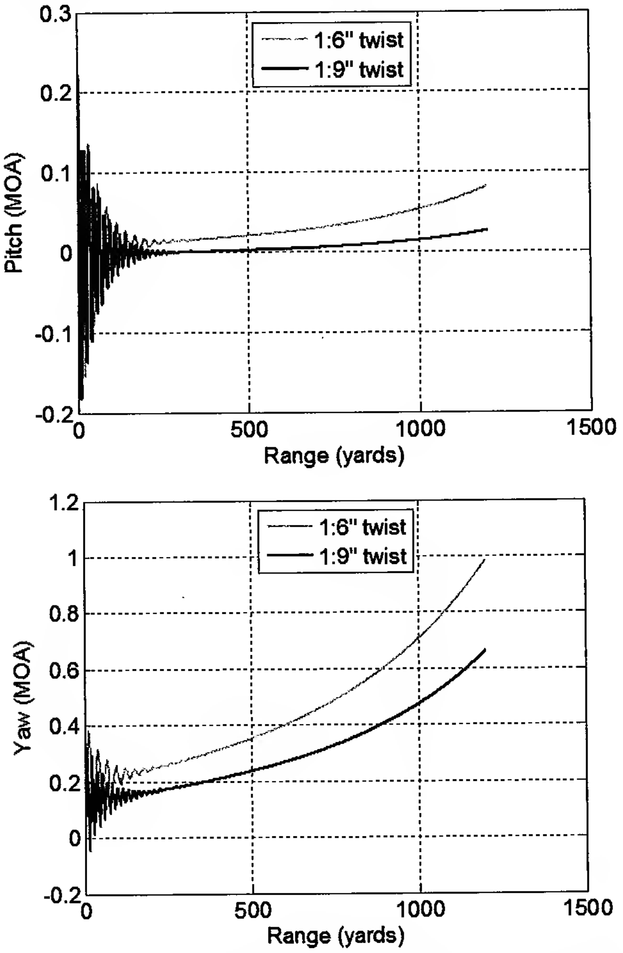


Figure 10.4. The yaw is much greater than the pitch as the bullet's axis bends with the long range trajectory.

The bullet is fired at 2800 fps at a 31.3 MOA angle above horizontal (about 27.8 MOA above a 100 yard zero) which zeroes the trajectory at 1000 yards, and the simulation runs for 1200 yards. At 1200 yards, the angle of the bullet's flight path is about 1.2 degrees below horizontal, dropping about 0.75" inch for every yard it travels. If the axis of the bullet were absolutely rigid, retaining the exact orientation that it left the muzzle with, the bullet would be flying with its axis at about a 1.7 degree angle to the flight path at 1200 yards.

Figure 10.4 shows the pitch and yaw of the bullet fired from two different twist barrels (1:9" and 1:6" twist), out to 1200 yards. Pitch is defined as the vertical angle that the nose makes with the flight path, and yaw is the horizontal angle that the bullet's nose makes relative to the flight path. The plot on the top shows the pitch of the bullet as it goes downrange, and the plot on the bottom shows the yaw. Note that the angles are *not* referenced to the ground, but are referenced to the bullet's flight path. In other words, at the end of the 1200 yard flight, the flight path of the bullet is 1.2 degrees below horizontal, and the axis of the bullet is pitched above the flight path by less than 0.1 MOA for even the highly stabilized bullet.

Note that the scales are not the same for the two plots. The plot on the bottom shows that the yaw of the bullet with respect to its flight path is more than 10X greater than the pitch for both the 1:9" and 1:6" twist barrels, *but it's still less than 1.0 MOA at 1200 yards.* With the bullet flying with its axis at less than a 1 MOA angle to the flight path, there will be no significant drag induced compared to a bullet that is flying with *zero* pitch and yaw. Furthermore, the difference in drag between a properly stabilized bullet and a highly stabilized bullet is insignificant. The predicted velocities at 1200 yards are within 0.1 fps for the 1:9" and 1:6" twist barrels.

The different levels of stability may not affect the drag in any significant way, but it can affect the trajectory. For example, the fact that the faster spun bullet flies with slightly more nose high pitch causes it to hit about 0.46" higher at 1000 yards when launched at the exact same initial angle. Think of this as vertical spin drift, or *lift drift*, and is practically irrelevant.

The majority of the bullet's misalignment with its trajectory is in the yaw plane. This is the effect mentioned earlier in the chapter on spin drift. When the bullet is forced to bend its spin axis with the trajectory, it reacts by pointing its nose to the right (for right twist barrels, left for left twist barrels). The yaw that results is known as the *yaw of repose*.

In Figure 10.4 you can see that the *yaw of repose* grows to about 0.65 MOA at 1200 yards causing 8.9" of spin drift at that range for the 1:9" twist barrel and almost 1.0 MOA of yaw for the 1:6" twist barrel which produces 13.3" of spin drift. The *squiggles* that you see in the first ~200 yards of the pitch and yaw plots is the precession of the bullet's axis as it struggles to start bending with the trajectory which begins to arc the instant the bullet leaves the muzzle. Once the bullet has transformed the torque on its axis from the vertical plane into a reaction that's mostly in the horizontal plane, the transient precession damps out, and the bullet settles down and just continues to increase the *yaw of repose* as the trajectory continues to bend. This may be what some shooters refer to as the bullet *going to sleep*. Once again I would like point out that the amount of initial pitching and yawing is imperceptible, and inconsequential to the bullets flight performance (0.4 MOA is less than 0.01 degrees).

The most important lesson to take away from this stability analysis is that *the bullet* ***does not*** *experience significantly more drag if it's flying with excessive stability.* The fear of increased drag due to 'over-stabilization' is really unfounded. It's true that a more rigid spin axis does affect the ability of a bullet to trace with the trajectory, but the effect is very weak. In the vertical plane, the slight nose-high pitch of the more heavily stabilized bullet causes it to hit only 0.46" higher at 1000 yards than the *ideally stabilized* bullet. This is an insignificant difference. The only significant way that a highly stable ('overly-stable') bullet affects the trajectory is thru added spin drift. In the above example, the spin drift predicted by the 6-DOF program was 8.9" and 13.3" for the 1:9" and 1:6" twist barrels at 1200 yards, respectively. The included ballistics software predicts 10" and 17" for the two barrels which is in error by a relatively minor amount. It's also interesting to note that the 6-DOF simulation calculated an SG of 1.44 and 3.23 for the two spin rates using all the details of the bullet's aerodynamics and mass properties, and solved using the full 6 DOF equations of motion. The Miller formula predicts 1.46 and 3.28, which is very good agreement for a much simpler prediction formula.

Gyroscopic stability and precision shooting

The previous section discussed in detail the effects of increased stability on a bullet's spin axis, and the consequences for the trajectory. It was established that a more stable bullet *does not* fly with its axis at large angles to the trajectory causing increased drag. So does that mean that there's NO downside to over spinning bullets? Not exactly.

The relationship between stability and precision is probably where the bulk of stability misconceptions exist. Gyroscopic stability can affect precision in two ways. First, if the bullet is not adequately stabilized, it will emerge from the muzzle and fly with some significant amount of yaw until it stabilizes (goes to sleep). This situation is bad for precision and adds significantly to the bullet's drag. This problem can be solved simply by insuring that the bullet is fired with sufficient stability by choosing a proper twist rate.

It's also possible for precision to be compromised if the bullet is spinning faster than it has to be for adequate stability. When a bullet emerges from the muzzle of a rifle, it's spinning very fast. Any imperfection in the shape, balance, or alignment of the bullet will cause it to disperse away from the bore line when it exits the muzzle. The amount of dispersion is related to how severe the imperfections in the bullet are, and also how fast the bullet is spinning. Higher spin rates produce more dispersion. This situation can create the illusion that the bullet's dispersion is *caused* by excessive stability, but that's not the reality. *The actual stability level of the bullet is not what causes the dispersion!* The imperfections in the bullet cause dispersion, and the dispersion is increased the faster the bullet is spinning. The more balanced the bullets are, the less dispersion will result from spinning them faster. One of the reasons why short range Benchrest shooters choose to shoot short, blunt, flat based bullets is because they require such a slow twist rate to stabilize. The slower twist barrels aggravate the imperfections of the bullets much less than faster twist barrels, and smaller groups result.

The relationship between spin rate and dispersion is stronger for low quality bullets. This is why British and British Commonwealth *Target Rifle* shooters used 1:14" twist barrels as until recently the discipline's rules required the use of *as issued* 7.62mm NATO military ammunition which was loaded with relatively poor quality 145 grain FMJ BT bullets. As precision bullet manufacturing technology matures and the resulting products move ever closer to having perfect balance, the relationship between spin rate and dispersion is diminishing.

There is much debate about what barrel twist rate or bullet RPM is *optimal* for precision shooting. The answer isn't as complicated as it's made out to be. The right way to choose the proper twist rate for a particular bullet is to select a twist that results in a stability factor (SG) of at least 1.5 at your intended muzzle velocity. If the stability factor is a little higher, that's ok. The effects of over spinning a bullet are not nearly as bad as under spinning it. If the SG is up near 2.0, that's not necessarily bad. As long as you're shooting good bullets there will be no detectable difference in precision. If you get a bad batch of bullets, a slower twist barrel may be more forgiving, but the difference would be hard to resolve.

Dynamic stability for spin stabilized projectiles

Up until this point, all of the discussion about stability has centered on gyroscopic stability. As shooters of spin stabilized bullets, it's important that we understand gyroscopic stability, but that's not *all* there is to the subject.

You may remember in the previous section, I stated that the gyroscopic stability of a bullet grows as the bullet flies downrange. It grows because the bullet's forward velocity decreases faster than its spin rate. This may have been a hard thing to accept for those long range shooters who have observed bullets *key-holing* in targets at long range. *Key-holing* is the term used to describe a bullet that leaves oblong shaped holes in the target as a result of tumbling, or flying with considerable pitch/yaw. Its common knowledge that bullets fired with adequate gyroscopic stability can become unstable at long range, tumble, and keyhole in the target. Most shooters assume that the problem is a lack of gyroscopic stability, and sometimes try to remedy it by using a faster twist barrel. A faster twist barrel certainly does increase the gyroscopic stability of the bullet both at the muzzle and downrange. However, ***when a bullet tumbles at long range, it's not because of a lack of gyroscopic stability, but through a lack of dynamic stability***.

Dynamic stability is altogether different from gyroscopic stability and is a much more complex subject. The factors affecting dynamic stability are more subtle, and most importantly, are greatly affected as the bullet slows down to transonic speeds (from around 1300 fps down to below the speed of sound at

~1120 fps). Some bullets are able to successfully negotiate the transonic flight regime and fly thru to subsonic without tumbling, while others will not have adequate dynamic stability to survive the large swings in aerodynamic forces and torques as they fly thru the punishing sound barrier. Because of the subtle nature of the things affecting dynamic stability, it's very hard to predict whether a bullet will or will not have adequate dynamic stability to fly properly through transonic speed. The only way to know for sure is experimentation. In general, heavier bullets with higher BC's are more likely to make it thru the transonic speeds, whereas lighter, smaller caliber bullets tend to have more trouble. In addition, boat-tailed bullets are more likely to be dynamically unstable in the transonic and subsonic regions. Very minor differences in boat-tail angle and length can have a big impact on a bullets dynamic stability.

Dynamic instability isn't always catastrophic. It's possible for a bullet to fly hundreds of yards with a dynamic instability, and not be overly affected. Remember the definition of stability is: the ability of a projectile to maintain its orientation in flight, and return to that orientation if disturbed. A bullet that's flying with a dynamic instability might simply have a very mild axis precession that only grows slightly over 1000 yards. Technically the bullet has a dynamic instability because it's flying with increasing pitch and yaw, but any adverse consequence may be minor. One bullet that exemplifies the consequence of dynamic instability is the .30 caliber Sierra 168 grain MatchKing. Due to its mass balance, and the particular dimensions of its boat-tail, this bullet suffers from a dynamic instability that causes it to develop significant amounts of yaw at long range. There is enough dynamic instability that the bullet is usually not effective beyond 800 yards unless it's driven to an extremely high muzzle velocity. *Most bullets used for long range shooting don't have problems with dynamic stability as long as they are flying above transonic speed (about 1300 fps).*

If a bullet has marginal dynamic stability at transonic speeds, it's sometimes possible to compensate with a faster twist. It's a similar situation to the bullet overcoming its basic static instability with adequate gyroscopic stability. If the bullet has a dynamic instability, you might be able to fix it by spinning the bullet faster, making the axis rigid enough to overcome both the static and dynamic instability of the bullet. It's easy to calculate the spin rate required to overcome static instability at the muzzle (supersonic speed). However, it's extremely difficult to calculate how much spin rate is required to overcome a dynamic instability caused by transonic flight. A few of the reasons are:

1. You can't accurately predict the amount of dynamic instability the bullet will have during transonic flight.
2. You can't accurately predict how much the spin rate of the bullet will have decayed by the time it reaches transonic speed.

For these basic reasons, it's not possible to predict the barrel twist that's required to overcome a dynamic instability. We can make the following qualitative statements: *A bullet might have poor dynamic stability as it approaches transonic flight. You may be able to overcome the dynamic instability by increasing the spin rate of the bullet, but it's hard to tell how much extra twist is required to overcome a dynamic instability at long range.*

A more complete discussion of dynamic stability and transonic effects is presented in the next chapter on Extended Long Range (ELR) shooting.

Conclusions

Gyroscopic stability is quantified with the gyroscopic stability factor: SG. The Miller formula is sufficiently accurate for predicting SG, and is built into the included ballistics program. The combination of barrel twist and muzzle velocity needs to produce a stability factor of at least 1.5 in order to insure adequate gyroscopic stability for a particular bullet. The consequences of marginal gyroscopic stability will show up as increased drag early in the bullet's flight as it struggles to go to sleep, and usually poor precision results. If the gyroscopic stability is way too low, the bullet will tumble soon after exiting the muzzle and never be able to right itself again.

Considering just the trajectory alone, the only consequence of spinning a bullet faster than necessary is increased spin drift which can be corrected for since it's a deterministic variable. The vertical strike of the bullet is not significantly affected, and the extra drag that's caused by the bullet flying with a stiffer spin axis is immeasurable.

In general, improved precision can be expected from slower twist barrels (as long as the twist produces satisfactory SG) because the slower spin rates don't exaggerate the components of dispersion that are caused by imperfections in the bullet. When using high quality bullets, there is little relation between spin rate and precision, assuming adequate stability.

Dynamic stability is different from static stability. Dynamic stability is challenged at transonic flight speeds, and can be responsible for bullets tumbling at long range. It may be possible to strengthen the rigidity of the bullet's spin axis enough to overcome dynamic instability, but the extra amount of spin that's required is difficult to predict.

Practical Advice to Take Away from this Chapter

This chapter contains some of the most in-depth material in the book. It's not necessary to have a complete understanding of it all to be successful at long range shooting. If you just remember some key points regarding stability, you will be able to avoid the common pitfalls.

1. Insure that your barrel twist produces a gyroscopic stability factor (SG) of at least 1.5 for the bullets you're shooting. SG can be calculated with the included ballistics program. Don't worry if SG is a little higher than 1.5, but don't choose rifling twist rates or bullets

whose combination produces an SG below 1.5 in the conditions you expect to shoot in.

2. Bullets that are properly stabilized will *go to sleep* quickly, without affecting flight performance (BC). If launched with adequate gyroscopic stability, they will fly with near zero pitching and yawing motion, and exhibit equal drag and BC from any rifle they're fired from.
3. Avoid the .30 caliber 168 grain Sierra MatchKing and other bullets with steep (greater than 10 degree) boat tails for long range shooting (over 800 yards). 168 grain bullets in different calibers or different designs are OK, but the Sierra 168 MatchKing has a unique dynamic instability that prevents it from flying properly at long range. The bullet provides excellent performance at short ranges, up to 600 yards.
4. Most bullets don't have problems with dynamic stability until they reach transonic speed (~1300 fps). As long as your bullet arrives at its target above 1300 fps, you shouldn't have to worry about dynamic stability at all. If you shoot at extended ranges beyond where your bullets will fall below 1300 fps, you *might* have a problem with dynamic stability. The only way to know for sure how a bullet will perform in transonic flight is to try it. As a rule, bullets that are heavy for their caliber and have shallow boat tail angles (less than 9 degrees) do better in transonic flight than bullets that are light for their caliber and have steep boat tails.

Chapter 11: Extended Range Shooting

Extended Long Range shooting, or ELR shooting, is defined differently by different people. ELR is commonly thought of as shooting beyond 1000 yards. Personally I don't like this definition because for many large calibers, shooting to 1000 yards is much easier from a ballistic performance point of view than shooting to 800 yards with a smaller caliber. For the purposes of this chapter, I'll define ELR shooting as: shooting at ranges where a portion of the bullet's trajectory has slowed to transonic speed, meaning near the speed of sound. This is more shortly expressed as: ***Shooting into the transonic***.

Understanding Transonic Effects

Air is a compressible substance. However, if a projectile is moving slowly, the air can get out of the way without compressing (path of least resistance). As the projectile moves faster and faster, the air has to move even faster to get out of its way. There is a limit to how fast air can move out of the bullet's way. That limit is the speed of sound. If the air can't get out of the way of the projectile fast enough, it has to compress. This compressed air is called a shock-wave.

Since a bullet is shaped like a wedge, it creates local regions of supersonic air flow even when the projectile is actually flying slower than the speed of sound. Bullets obviously slow down after firing. But suppose you imagine a projectile starting from rest and accelerating. It will get up to about 890 fps before the air begins compressing. The speed at which air becomes compressible depends on the bullet shape. If the bullet is blunt, the air will have to become compressible at a lower speed than if the bullet is pointy. In other words, transonic speed is actually slower for a blunt bullet than for a pointy bullet.

As the projectile accelerates thru the sound barrier, the shockwave strengthens. Eventually the bullet will develop fully supersonic airflow all around it, and will be completely in the *supersonic flight regime*. This will occur at about 1340 fps, again depending on the projectile shape and atmospheric conditions.

The range of flight speeds where the airflow around the bullet is transitioning from compressible (fast) to incompressible (slower) is known as the *transonic* flight regime. Said another way, when the bullet is moving at a speed close to the speed of sound (near Mach 1), it is in the transonic region.

I chose to define ELR shooting according to transonic effects because it's in this flight regime that all kinds of new factors become involved in understanding and predicting the trajectory of the bullet. When it comes down to it, ELR shooting is about understanding and dealing with transonic effects.

Transonic effect on bullet drag

One of the most obvious effects of transonic aerodynamics is the effect on the bullet's drag coefficient. Here I'll refer to a figure presented earlier in Chapter 2 which shows the drag curve for a typical long range bullet.

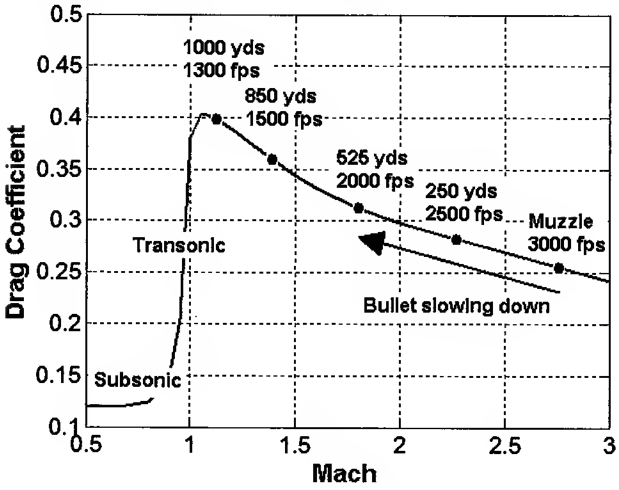


Figure 11.1. Drag curve goes thru massive transients at transonic speed.

Notice how the drag coefficient slowly increases[17] as the bullet slows down, peaks just before Mach 1, then abruptly drops off to its subsonic value. The sharp rise in the drag curve at transonic speed is due to the fact that the bullet has to do extra work to compress the air into a shockwave. This expenditure of energy isn't required at subsonic speed which is why the drag coefficient is so much lower there.

The dramatic swing in drag coefficient is one of the things that makes it challenging to shoot into the transonic regime. The reason this is so troubling is because it's very difficult to predict what the exact shape of the drag curve will be for any given bullet. Thru the use of BC's, we reference the drag of our projectiles to a standard projectile (the curve shown in Figure 11.1 is for the G7 projectile). This match serves us well at supersonic speed where the curve is fairly well behaved and similar for many bullets. However, when the bullet slows below Mach 1.2 (about 1340 fps, near the peak) the shape of our bullet's drag curve can begin to diverge from the standard curve significantly due to small differences in the bullet's geometry. Said another way, *the small*

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[17] Remember that although the drag *coefficient* is increasing as the bullet slows to transonic, the actual *force of drag* is diminishing because of the lower flight speed.

differences in shape between a given bullet and the G7 standard can lead to significant misrepresentations of drag for that bullet at transonic speed.

So how does a shooter deal with this discrepancy between drag curves? One way is to reference the BC to a different standard that may be more fitting for a given bullet shape (G2, G5, G7, etc.). Several ballistics programs are available that accept BC's reverenced to these other standards.

Another way would be to calculate a trajectory using a drag curve which is created specifically for an individual bullet. The following section will explain the use of *custom drag profiles* for individual bullets.

Custom Drag Profiles

As stated previously, the use of BC's to reference the drag of a bullet to a standard (G7) is very useful for predicting accurate trajectories in the supersonic range of the trajectory. However, due to variations in the drag of a bullet near transonic speed (such as encountered in ELR shooting), the use of BC's can produce inaccurate results. The inaccuracy arises because the peak of the drag curve can be very different based on minor differences in the shape of the bullet. In order to predict a bullets trajectory into and beyond transonic flight speed, the use of custom drag profiles is required.

A *custom drag profile* is a drag curve that's developed specifically for a given bullet, based on its unique shape. In other words, a custom drag profile is a specific representation of a specific bullets' drag at all speeds. This is different from the use of BC's where the drag curve of a bullet is simply a scaled version of the standard bullets drag curve.

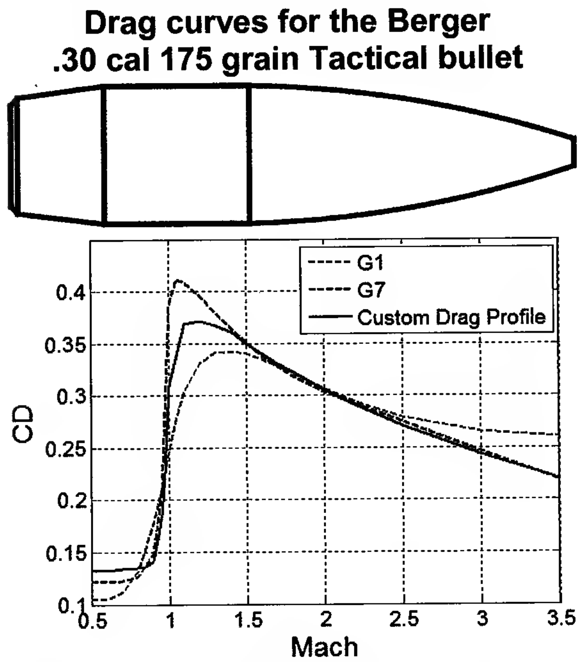


Figure 11.2. Custom Drag Profile compared to scaled G1 and G7 curves.

Figure 11.2 shows three drag curves for the Berger .30 caliber 175 grain Tactical bullet: the G1, G7 (scaled for this bullet), and the custom drag profile. Since the shape of this bullet is close to the G7 standard projectile, the custom drag profile (solid black line) and the G7 curve are very close to each other from Mach 1.4 (1562 fps) and up. That means that between the muzzle, and whatever range the bullet slows to ~1562 fps (i.e., normal *long range* shooting) the G7 BC based trajectory prediction will be spot on.

However, this bullet is not shaped *exactly* like the G7 standard projectile. As a result, the drag curves begin to diverge somewhat below Mach 1.4. *The divergence between the G7 curve and the actual bullets drag curve manifests as error in a G7 BC based trajectory prediction if the range exceeds that which the bullet slows below Mach 1.4.*

For *normal* long range shooting where the bullet remains supersonic, the gap between the G7 standard curve and any given long range bullet is small enough that it doesn't result in significant error in predicted trajectories. However, for those trajectories that extend into the transonic and subsonic flight region (as in ELR shooting), the difference between the drag curves at those speeds can be large enough to introduce significant error in the predicted trajectory.

So how does a shooter manage the problem of drag prediction at transonic speeds? Unfortunately, custom drag profiles would be required for each and every bullet, just like BC's (only tables of data rather than single numbers). As an experiment, I developed the custom drag profile for the bullet shown above (the Berger 175 grain Tactical bullet) and put it to the test by shooting it thru transonic, and into subsonic.

Figure 11.3. The LaRue OBR was used for the ELR drop test because of its extraordinary precision, and the fact that it shoots transonic-stable bullets at a low enough MV to be subsonic at 1000 yards.

Three charges were loaded and fired from a 20" barreled LaRue OBR. The loads were: Max for the 20" barrel (2570 fps), and two lower charges intended to mimic max velocities for the 18" and 16" barreled LaRue OBR's. Velocities were 2520 fps (max from 18" barrel) and 2470 fps (max from 16" barrel). The three loads were fired at 1000 yards in winter, sea level conditions (worst case scenario for stability and air density). Under these conditions, the bullets were going transonic between 800 and 900 yards, and had between 425 and 470 inches of drop. The bullets remained stable thru the transonic portion of their flight.

The OBR produced 5-shot groups with vertical spreads of less than one MOA with all 3 loads at 1000 yards. *The center of each group was within 1" of the predicted drop based on the custom drag profile.* Note that the trajectories predicted by the G1 and G7 BC's under these same conditions were in error by between 8" to 10". This error in the BC based predictions is due to the mismatch in the transonic drag curves between the standard curves and this bullet (Figure 11.2).

This high level of accuracy in trajectory prediction at ELR (transonic) range is only possible with custom drag profiles that are based on direct testing of individual bullets. Unfortunately, most ballistics programs are only set up to handle conventional BC based solutions. Even if a program was capable of running custom drag profiles, generating accurate custom drag profiles for many bullets is not an easy task.

The uncertainty of the bullets' drag curve at transonic speeds is one issue the ELR shooter has to contend with, but unfortunately it's not the only problem. In fact, it's relatively minor compared to the stability considerations of ELR shooting.

Transonic effect on bullet stability

The greatest challenge of ELR shooting is dealing with transonic effects on bullet stability. In the previous chapter, we covered gyroscopic stability in great detail, and briefly touched on dynamic stability. I'll present the following as a quick reminder to get us back into a stability discussion:

1) Gyroscopic stability is the easy one to predict. Mathematically, the gyroscopic stability factor (SG) has to be above 1.0 at the muzzle for the bullet to be stable. It's recommended to keep the SG above 1.5 as a safety margin. SG increases as the bullet flies downrange because the forward velocity (destabilizing factor) is decaying faster than the rotational rate (stabilizing factor).
2) Dynamic stability is more difficult to predict because it depends heavily on aerodynamic properties that are very difficult to calculate or estimate accurately. Dynamic stability is characterized by the dynamic stability factor (SD), and it becomes increasingly important as the bullet approaches transonic speeds where the aerodynamic transients are most dramatic.

Bullet stability is the #1 consideration for bullet flight in the transonic regime, so this is a subject we'll be spending quite a bit of time on. To facilitate our study of transonic bullet stability, we'll be using what's known as a stability map to illustrate many of the dynamics.

An example stability map is shown here in Figure 11.4. This stability map is for a Berger 7mm 180 grain VLD fired at 2800 fps from a 1:9" twist barrel in standard conditions. The thick black line represents the boundaries of stability, and the stable region is inside the horseshoe-shaped "bowl". The gray line inside the horseshoe represents the bullet's stability condition. Each 100 yards is marked with a black circle.

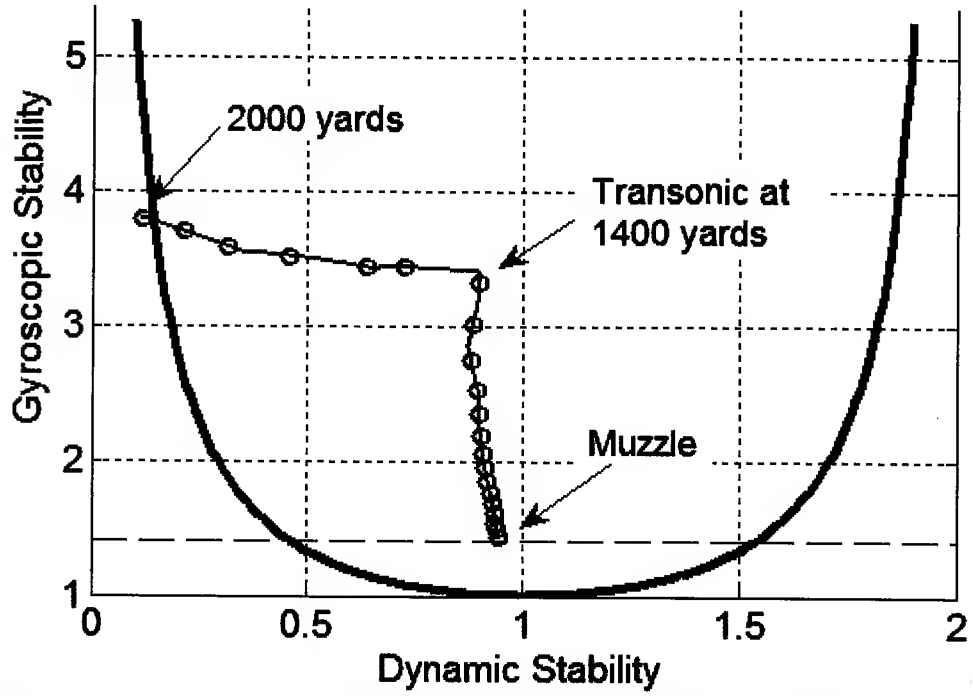


Figure 11.4. Gyroscopic Stability Factor SG vs Dynamic Stability (SD).

More specifically, inside the horseshoe, the bullet is gyroscopically and dynamically stable. Below the 1.0 line, the projectile is gyroscopically unstable, and it should be above the dashed line at 1.4.

In this stability map, you can see the stability condition of the bullet is very good from the muzzle to 1400 yards, which is where the bullet goes transonic. Due to the dramatic aerodynamic transients at transonic speed, the stability takes a sharp turn for the worse, and heads straight for the edge of the horseshoe. Despite this rapid divergence, the bullet's stability condition remains good all the way until just before 2000 yards. At that point, the bullet becomes *dynamically unstable,* which is indicated by the fact that the trace has left the horseshoe.

You can see the gyroscopic stability starts out just above 1.4, which is good. The dynamic stability starts out at just to the left of 1.0 (horizontal axis), which is a good value for SD. The extent of acceptable SD ranges from 0 to 2, but must stay within the horseshoe. ***If the stability condition of the bullet strays out to the left or right of the horseshoe, it indicates a condition of dynamic instability.*** That means the bullet will begin to gyrate at increasingly large angles until it tumbles. The bullet won't necessarily tumble the moment it leaves the horseshoe, but it does indicate a degrading condition in which the pitching/yawing motion of the bullet is increasing rather than staying at zero.

If the bullet's stability condition leaves the bottom of the horseshoe, that indicates a lack of gyroscopic stability and will result in immediate, catastrophic tumbling.

The trace which indicates the bullet's stability condition will always start out low, and move up (indicating an increase in gyroscopic stability), and usually to the left. In order to maintain dynamic stability, the trace must stay within the horseshoe (the trace tends to move towards the left side, towards low dynamic stability).

I'm intentionally being redundant with these explanations because the stability map will be the most important learning tool for understanding transonic stability effects which are so important to ELR shooting.

Effects of twist rate on transonic stability

It's commonly believed that increasing the twist rate will improve a bullet's chances of remaining stable at transonic speed. There is considerable truth to this statement, but the difference might not be as pronounced as commonly thought, and there are very long bullets that cannot be stabilized no matter how fast the spin.

The stability map shown here in Figure 11.5 has traces for the same 7mm 180 grain bullet fired at the same muzzle velocity and same atmospheric conditions, but illustrates the effect of firing that bullet from a 1:8" twist barrel vs a 1:9" twist barrel.

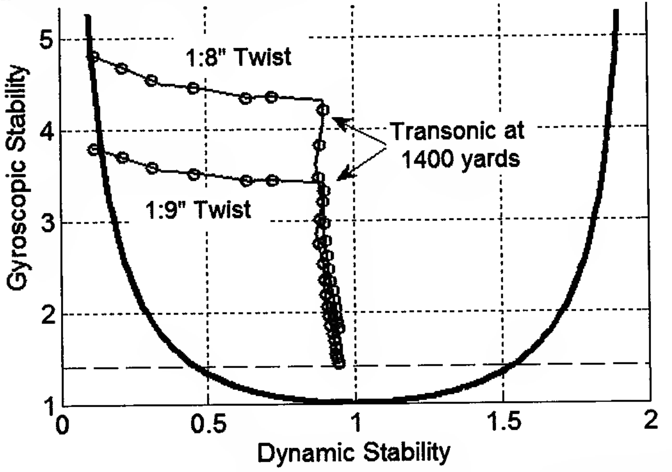


Figure 11.5. A faster twist rate will increase gyroscopic stability, but can't always overcome dynamic instability.

Notice that at the muzzle (bottom of the trace) that the 1:8" twist condition starts out with a higher gyroscopic stability factor, about 1.9 compared to the 1.4 that's achieved with a 1:9" twist. Also note that the 1:8" twist trace is much higher than the 1:9" twist trace by the time the bullet goes transonic at 1400 yards. At this point, there is a bigger difference in the SG in favor of the 1:8" twist, about 4.2 compared to 3.3. As the traces approach the left edge of the horseshoe, it's clear that the 1:9" twist stability condition will leave the shoe first because the horse-shoe is more narrow down low compared to up high.

The previous is a visual description of how the lines trace around on the stability map. A technical way to say the same thing is: increasing the twist rate from 1:9" to 1:8" increases the *gyroscopic stability* at all points in the bullets flight. However, the increase in spin rate does not affect the bullets *dynamic stability* very much. In other words: ***It is often possible to increase the gyroscopic stability enough to compensate for low dynamic stability.*** However, you can see from the stability map in Figure 11.5, the increase from 1:9" to 1:8" twist means that the bullet's stability condition stays *good* for only an additional ~30 yards at the end of a 2000 yard trajectory (the circles on the gray lines represent 100 yard increments, with the max range being 2000 yards).

If another case were run at a lower twist rate, say 1:10" twist, that bullet's stability condition would leave the horseshoe even sooner, possibly 100 yards or more sooner due to the more rapid curvature inside the horse-shoe at lower levels of gyroscopic stability.

To summarize this section, we can say that you can usually extend the range of stable bullet flight into and past the transonic flight regime by using a faster twist. However, there is a point of diminishing returns as you increase the initial SG thru twist rate.

Effects of bullet shape on transonic stability

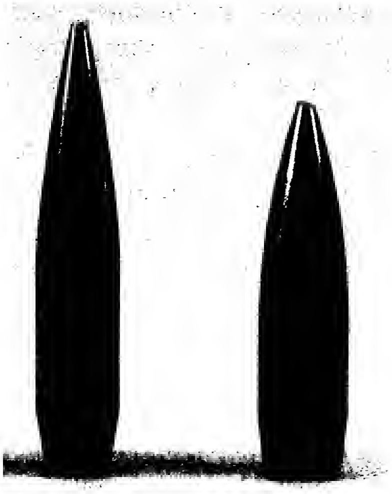


Figure 11.6. Long bullets are inherently less stable than shorter bullets.

The 7mm 180 grain Berger is a relatively long and skinny bullet. From a stability point of view, we could call this bullet *tipsy* compared to a shorter fatter bullet. Refer to the previous chapter to Figure 10.1 for a schematic of why long bullets are less stable than short bullets (it has to do with the center of pressure and center of gravity being further apart on long bullets).

In Figure 11.6, the Berger 7mm 180 grain VLD is compared to the Sierra .30 caliber 175 grain MatchKing. It's obvious that the 7mm bullet has a higher BC than the .30 caliber bullet in this comparison. It should be equally obvious that the .30 caliber bullet has greater stability than the 7mm bullet. For normal long range shooting applications where the terminal velocity of the bullet remains supersonic, the 7mm bullet would clearly be the better performer of this pair. However, in ELR shooting where transonic stability is a major concern, the shorter, fatter .30 caliber bullet has an important advantage.

We know just from the required twist rate for these two bullets that the .30 caliber 175 grain bullet is easier to stabilize. The 7mm 180 grain bullet needs a 1:9" twist, whereas the .30 cal 175 grain projectile is comfortable from a 1:13" twist. The fact that the .30 cal bullet is easier to stabilize from the muzzle indicates that it is inherently more stable at all speeds, including transonic and subsonic.

Figure 11.7 compares the stability map for the 7mm 180 grain bullet fired from its recommended twist of 1:9" to the .30 caliber 175 grain bullet fired from the common 1:12" twist. Both trajectories are run to 2000 yards.

It's important to fully understand the trade-off between the 7mm and .30 caliber bullets that are used as examples here. The 7mm 180 grain bullet enjoys a dramatic advantage in ballistic performance for its entire range of supersonic flight. However, soon after entering the transonic regime, stability rapidly begins to decline. On the contrary, the shorter .30 caliber bullet which is a relatively poor performer in the supersonic flight envelope is much more comfortable in the transonic and subsonic flight regimes where stability becomes important.

Note that the trace for the 7mm bullet is heading rapidly to the left at 2000 yards. This indicates a condition that is more likely to result in catastrophic tumbling soon after becoming dynamically unstable. On the contrary, the .30 caliber bullet has much greater gyroscopic stability (6.1 vs 3.9) as it crosses the boundary of stability at 1700 yards. Also, the .30 caliber stability trace is trending up as it crosses the horse-shoe line much more than the 7mm trace. This indicates that although the .30 caliber bullet will become dynamically unstable by definition, it may not result in immediate and catastrophic bullet tumbling, but rather a slow and gradual build up of yaw.

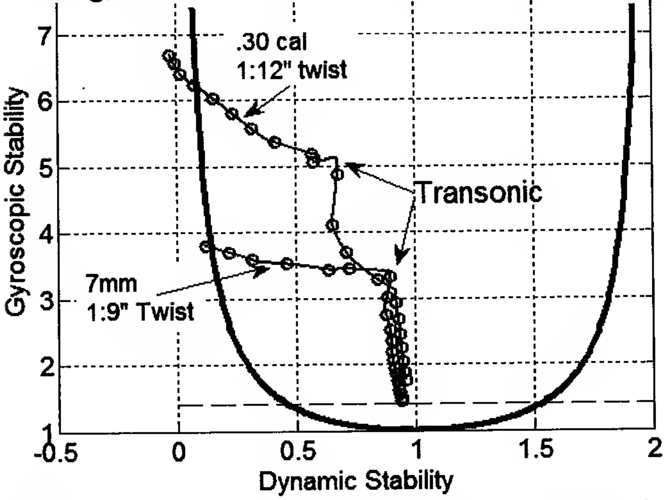


Figure 11.7. The .30 caliber trace exits the horseshoe (stable region) at 1700 yards, whereas the 7mm trace exits more abruptly just before 2000 yards. Note that the .30 caliber trajectory was subsonic for a longer time and distance before becoming unstable.

The principle of trading off supersonic performance for transonic stability is a common theme in ELR ballistics. For example, the .338 caliber 250 grain match bullets from Lapua and Sierra are out-performed by their 300 grain counterparts from muzzle to transonic range. However, the 300 grain bullets can become more or less *tipsy* depending on atmospherics, muzzle velocity, and other sensitivities even when fired from a 1:10" twist barrel. On the contrary, the 250 grain bullets lose velocity quicker and encounter transonic effects at a shorter range, but they enjoy an incredibly high level of stability and usually have no problem surviving the challenges of transonic flight. In other words, if you want to optimize performance from the muzzle to about 1500 yards, the 300 grain option is best. However, if you want a predictable and reliable capability beyond 1500 yards (beyond where both projectiles are transonic) the shorter, more stable 250 grain bullet is the better option.

Back to the stability map in Figure 11.7. You'll notice that the 7mm trace exits the stable region just before 2000 yards. The .30 cal trace exits the stable region (less abruptly) at about 1700 yards. The relative velocities for where these two traces exit the stable region are: 870 fps for the .30 cal, and 950 fps for the 7mm. Again, this illustrates that the more stable .30 caliber round remains stable to a lower flight speed than the 7mm.

Intermission: A word about the modeling

Some readers may be curious about the source of the data presented in the stability maps which are so important to the understanding of transonic stability and ELR shooting. The data was generated using a 6 Degree Of Freedom (6-DOF) computer simulation.

A *normal* commercial ballistics program models projectile motion in 3 degrees of freedom: up-down, left-right, back-forth. In other words, it models the linear motions of the projectile. This kind of modeling only requires the drag of the projectile to be known. This is usually accomplished thru the use of a BC.

A 6-DOF program also includes the 3 angles: pitch, yaw, and roll, and requires a far more complete aerodynamic model for the projectile. It should be noted that the aerodynamic data required to model the 6 degrees of freedom and stability of spin-stabilized projectiles are extremely difficult to predict with reasonable certainty, even using the best modern tools. In other words, the data presented in the stability maps in this chapter may be quite inaccurate for the projectiles they represent.

You might ask: why would I present data that I know to be inaccurate? The answer to that question is easy if you understand the nature and utility of modeling. My intent in presenting this information is to illustrate the *trends,* the important *variables,* and their *effects* on the general stability characteristics for different classes of bullets. In other words, the fact that a faster rifling twist rate can help, but maybe only a little is adequately demonstrated in Figure 11.5, even if the exact range at which the projectile exits dynamically stable flight might be off by a couple hundred yards. Likewise, the *picture* of stability for a long narrow bullet compared to a short fat bullet is valid, even if the exact numbers aren't precisely valid.

As you examine these stability maps, please remember they are presented in order to communicate ideas. The exact numeric data presented in them are approximate, and only intended to illustrate trends.

With this in mind, we'll continue examining the factors that affect the transonic stability and ballistic performance of bullets flying in and below transonic flight speeds.

Effects of different rifling types on transonic stability

Rifling in the barrel is obviously necessary to impart the proper spin to a bullet in order to achieve stability. Barrels do this very well with a variety of different land/groove configurations including: 3, 4, 5 or more grooves, thick and thin, contoured or '5R', gain twist, etc. They all achieve their goal of spinning the bullet at the desired rate. However, these different characteristics also have unintended consequences which are negligible for normal long range shooting where the bullet is supersonic, but become important when the bullet enters transonic flight in ELR shooting.

The rifling has two effects which are important to ELR shooting. One is the effect the rifling has on how quickly the bullet's spin rate decays. You can imagine that a deep rifling with sharp edges will cause the spin rate to decay faster than a shallow smooth rifling. The rate of spin rate decay is important to the bullet's stability condition as it enters transonic flight far downrange. You can fire the same type of bullet from two barrels, and due to differences in the grooves that are engraved on the bullet, one bullet can retain more of its spin at extended range and have better stability than the other.

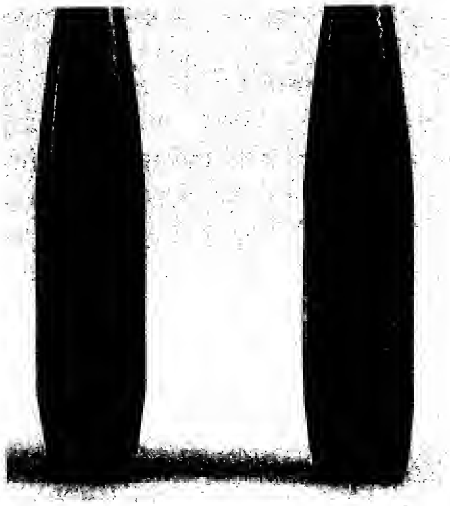


Figure 11.8. Rifling engravings matter, but not a lot.

The other effect of rifling on stability is related to the aerodynamic properties known as the Magnus force and moment. A full description of the Magnus force and moment is beyond the scope of this book. Here's a short explanation: The Magnus force arises from the interaction between the spinning surface of the bullet including the rifling, with the boundary layer of air flowing around the bullet. It's the same force that causes curve balls to curve. The center of pressure for the Magnus force is highly dependent on Mach number, and shifts a great deal as the bullet goes transonic. This dramatic change in the Magnus CP is the biggest reason for why dynamic stability is challenged so badly at these speeds. Unfortunately, because the Magnus force is developed within the boundary layer, it is strongly influenced by the geometry of the rifling which are engraved in a bullet.

The first of these effects (the effect of rifling on spin rate decay) can easily be modeled with the 6-DOF program simply by making manual adjustments to the aerodynamic coefficient known as the *roll damping* coefficient.

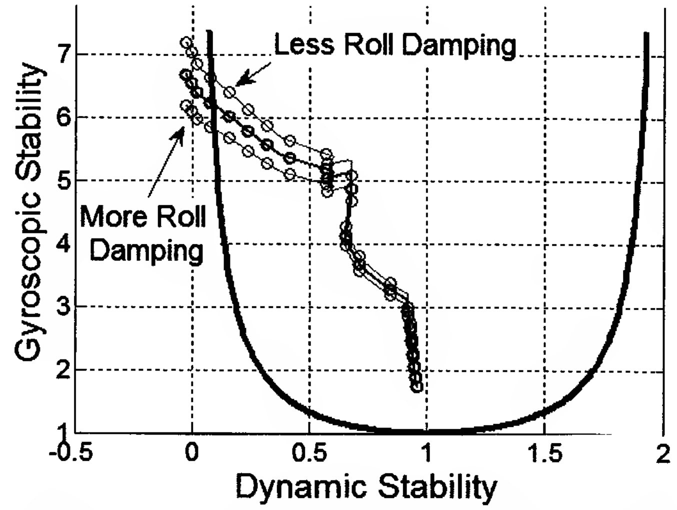


Figure 11.9. The specific nature of the rifling grooves imparted on the surface of the bullet have a very minor effect on the bullets rate of spin decay.

The stability map shown in Figure 11.9 has 3 stability traces on it. All 3 are for the .30 caliber 175 grain bullet modeled previously (fired from a 1:12" barrel). All 3 traces are generated with the exact same conditions with the exception that the roll damping coefficient was manually adjusted by +/- 10%. This simulates the bullet being fired from barrels that impart more or less aggressive rifling on the bullet which affect how quickly the rotation rate of the bullet decays.

The middle trace was generated with the nominal roll damping as predicted by the aerodynamic model. The trace just above it indicates a greater level of gyroscopic stability because it was run with the roll damping coefficient lowered by 10%. In other words, the bullet is retains its spin rate better and has greater gyroscopic stability as a result. The bottom trace was run with 10% greater roll damping, which decays the spin rate faster, and results in lower gyroscopic stability for the bullet.

Note that both bullets are fired with the same initial spin rate, and it takes a while for the difference in roll damping to have an effect on the gyroscopic stability. By the time the bullets reach transonic speed, the bullet with the lower roll damping (smoother, shallower rifling) will have retained 83% of its original spin rate, while the bullet with the higher roll damping (rougher, deeper rifling) retains only 79% of its original spin rate.

This is a small effect, but can be a reason why different barrels produce different transonic performance with ammunition and conditions that seem to be the same.

Also note that the retained velocity at this range is only 40% of the muzzle velocity compared to the ~80% retained spin rate. This fact is the reason why the gyroscopic stability grows so much as the bullet flies downrange. At the point where the bullet reaches 1100 yards, it's spinning at a rate of 1 turn in 5.9".

Live fire testing of twist rate effects on stability and drag in transonic flight

In the book *Modern Advancements in Long Range Shooting – Volume 1,* I've published the results of live fire testing which shows how different twist rates affect a bullets transonic drag. Also, how the different rifling profiles affect the bullets RPM decay. Numerous examples of real world test results are presented which provides much more detail regarding transonic stability and drag. For anyone interested in researching this matter further, refer to *Modern Advancements in Long Range Shooting – Volume 1.*

Effects of atmospherics on transonic stability

Atmospherics will affect the transonic stability of bullets in several ways. The two most important atmospheric effects are pressure and temperature.

Pressure is most closely related to altitude, so the following stability map is presented with 3 traces corresponding to the standard ICAO air pressure and density at sea level, 5,000 feet and 10,000 feet. Notice the dramatic effect that altitude has on the stability map. At sea level, the bullet exits the stable region of the map at about 1700 yards. At 5,000 feet altitude, the trace stays within the stable region almost all the way to 2000 yards. At 10,000 feet altitude, the trace remains comfortably stable all the way up to 2000 yards with a lot of room to spare.

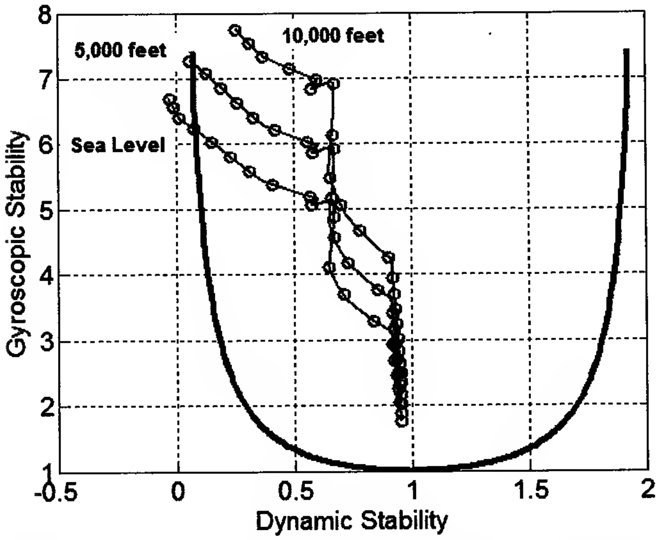


Figure 11.10. Atmospheric effects, specifically altitude, have a major effect on the trans and subsonic stability of a bullet. Air density is the root cause that affects stability.

Shooting at high altitude can produce much better ballistic performance all thru the normal supersonic flight range of the bullet. There are two separate effects working together as the altitude increases, and both effects are favorable to the bullets flight. Both result from the thinner (lower density) air.

The first effect is simply that since the air is less dense at high altitude, the bullet retains velocity better, and takes longer (travels farther) before entering transonic flight.

The second effect is that as the bullet finally slows to transonic and then subsonic speed, the lower density air creates less of a de-stabilizing force for the bullet to deal with. In other words, the source of the bullets stability is that the spinning mass makes the axis of the bullet rigid. This *stabilizing force* is the same at all altitudes because it's tied to the bullet's mass. However the *de-stabilizing force* acting to overturn the bullet is aerodynamic, and the strength of that force is related to the density of the air. Lower density air means less destabilizing force, and a more stable bullet.

The effects of temperature alone are also interesting to think about, but amount to very little consequence. A higher temperature will have offsetting effects on a bullet's flight performance at long range when transonic speeds are a consideration. First, an elevated temperature will reduce the air density (all else being equal), which improves the bullet's flight by allowing the bullet to go farther before encountering transonic speed, as well as slightly reducing the severity of the de-stabilizing forces at transonic speed. The other effect of elevated temperature is that the speed of sound is *higher*. This means the bullet will encounter transonic effects at a higher velocity than it does when the air is colder. In the end, these two effects cancel each other out almost totally, and there is little net effect of a temperature change on a bullet's stability level. The temperature will affect the trajectory by a significant amount, only thru its affect on air density and speed of sound, but not so much the quality of the bullet's stability. When stability maps are run for a nominal temperature and +/- 30 degrees F, the traces all lie nearly on top of each other.

Final remarks on transonic stability

The important ideas to retain from the several previous sections are:

- Ballistic performance at transonic ranges is highly dependent on transonic stability which is very difficult to predict.
- Short fat bullets, typically with lower BC's, are more likely to have reliable capabilities at transonic speeds than longer pointier high BC bullets. This is a trade-off because the lower BC bullets have shorter supersonic ranges, and worse performance everywhere until transonic.
- Increasing the rifling twist rate can increase the *gyroscopic stability* of a bullet for its entire trajectory. Depending on how *tipsy* the bullet is to begin with, the increased spin rate may or may not help the bullet remain *dynamically* stable thru the transonic region.
- The specific geometry of the rifling that a barrel engraves on a bullet can affect its transonic stability thru affecting the bullets spin decay. This is a relatively minor effect.
- Atmospherics, especially altitude, have a huge effect on a bullets transonic stability and flight quality.
- *Modern Advancements in Long Range Shooting – Volume 1* presents extensive test results on the subject of transonic stability and rifling effects.
- Bottom line; if you want to insure favorable and predictable bullet flight into and thru transonic speeds, fire short bullets from fast twist barrels with shallow, smooth edged rifling at high altitude.

Other considerations for ELR shooting

Transonic stability is the biggest challenge of ELR shooting, but it's certainly not the only challenge. When shooting to extended ranges, some factors become important that aren't necessarily big considerations for *normal* long range shooting.

For example, a scope base with 20 MOA of taper and a scope with 70 MOA of internal adjustment will get you about 55 MOA of available elevation adjustment which is plenty for *normal* long range shooting. It will certainly get you out past 1000 yards with most reasonable cartridges and bullets. However, as the bullet slows way down out there and the flight times extend beyond 2 or 3 seconds, the amount of bullet drop becomes so excessive that you have to figure out how to adjust for the extraordinary amount of drop.

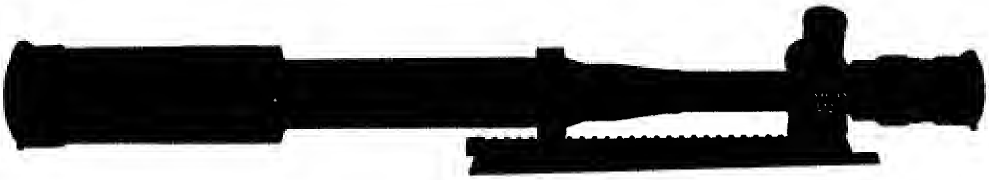


Figure 11.11. Scopes with external adjustments like this US Optics SN9 have more elevation travel than scopes with internal adjustment because the reticle movement is not constrained by the internals of the scope tube.

For example, a typical trajectory for a .30 cal 175 grain bullet will require about 33 MOA of elevation to zero at 1000 yards which isn't a problem in most normal set-ups. By 1300 yards, the trajectory requires over 57 MOA to be zeroed. This is an amount that might begin to stress the available elevation in many long range optical systems. In just another 100 yards, at 1400 yards, the bullet is down to 67 MOA, then 78 MOA at 1500 yards. At 1500 yards, the bullet is dropping at a rate of about 10 MOA per 100 yards. Such a dramatic amount of elevation can require the use of some creative scope

Figure 11.12. High quality laser rangefinders are a necessity for ELR shooting where the slightest uncertainty in range can cause huge miss distances due to the rapidly falling trajectory.

mounting hardware with large amounts of built in taper to allow the scope to zero at longer ranges. Of course when you mount the scope at a large enough angle, it prevents you from being able to zero the rifle at close range which renders it useless for the closer ranges.

The incredible rate of bullet drop causes problems for other reasons as well. Consider the consequence of a range uncertainty. At 1000 yards with the .30 cal trajectory, a range measurement error of +/-10 yards will amount to about +/-7" of miss distance. However, at 1500 yards, a +/-10 yard error in range results in +/-18" of miss distance! In other words, at 1500 yards, the bullet is dropping at a rate of 1.5 feet for every 10 yards of travel.

Considering that typical laser rangefinders have a diverging beam and weaker signal returns at extended range, it can be difficult to get an accurate range to a target that's 1500 yards away. There might be exceptions where the target is highly reflective, located in favorable terrain and the atmospherics are clear, etc. However the optimal conditions that allow accurate ranging at extended ranges are the exception rather than the rule. This goes for commercial grade laser rangefinders. There are units available to the military which are far better at ranging out to incredible distances, but these are very expensive and generally not available to the public.

When a shooter needs to know an accurate distance to a target at 1500 yards or farther, other creative means are often employed. GPS imagery, for example, can be downloaded, printed, and carried in the field. Or, if a signal is available, a laptop can be taken afield to get the imagery on site. Handheld GPS units can be used by storing waypoints at a target's location and the GPS can calculate the distance from the shooter to the waypoint.

The various methods for determining ranges to such distant targets usually have several things in common: they're slow; require cumbersome or delicate equipment; are not capable of pin-point accuracy; and are not practical for determining the range to non-cooperative or *live* targets. Bottom line: unless you have access to a high end military laser rangefinder, determining the exact range to target will be a significant problem for ELR shooters.

Another problem caused by the rapidly falling trajectory is the sensitivity to variations in muzzle velocity. Going back to our .30 cal 175 grain trajectory, the bullet has 1,230" of drop at 1500 yards when fired at 2800 fps muzzle velocity. We all know that muzzle velocity varies within limits. A typical muzzle velocity spread for *good* long range ammo is 30 fps (average +/- 15 fps). With this much variation in muzzle velocity, the bullet's point of impact will be +/- 16", or 32" of total vertical dispersion from just the muzzle velocity variation alone. Of course the sensitivity is less for larger, higher performance cartridges like the .338 Lapua Mag, or a large 7mm magnum with high BC bullets. However the problems caused by the rapidly falling trajectory at extended ranges become serious at some point or another no matter how big the cartridge is.

Elements like Coriolis and spin drift also become more important and *need* to be corrected for. The trajectory becomes increasingly sensitive to rifle cant and wind. Even variations in bullet-to-bullet BC can introduce significant dispersion when shooting into the transonic. Basically every element of external ballistics that was covered in the first 10 chapters becomes exponentially more critical in ELR shooting.

Summary and important conclusions for ELR shooting

- Standard BC based trajectory predictions may have significant error when the bullet slows to transonic speeds. This can only be addressed using custom drag profiles that models the drag for each specific bullet at all speeds.
- Some of the longer bullets will not remain stable thru transonic speeds which results in loss of accuracy and the bullets not flying predictable trajectories. Sometimes a medium weight bullet that's shorter actually has greater capability at extended ranges because of its ability to maintain stability and a predictable flight path thru transonic.
- Barrel twist rate and the grooves engraved on a bullet can have a minor effect on a bullets transonic stability. However the biggest issue is atmosphere. A bullet that doesn't have a chance of staying stable thru transonic at sea level might have no problem at 5,000 feet altitude due to the lower density air.
- Excessive and rapid bullet drop at ELR introduce challenges for the shooters optics.
- Accurate rangefinding at ELR distances becomes increasingly difficult and increasingly critical.

Summary of the Elements

The preceding chapters have gone into considerable detail on the important fundamental elements of external ballistics for small arms shooting at long range. The purpose of this summary is to help the shooter identify the relative importance of the various elements so they can be prioritized and addressed in the appropriate order. For example, it would be inappropriate to be more worried about Coriolis effects than gravity drop. This summary will attempt to present the relative importance for the elements of external ballistics. Keep in mind this is a subjective list. Items may shift position in the list in some circumstances, and some shooters may order them differently. This is my list based on my own knowledge and unique experiences.

1. **Gravity Drop**

At the top of the list, without a doubt, is gravity drop. Drop is the most fundamental and basic problem for the long range shooter to address. At the most basic level, accounting for drop simply means measuring the distance, calculating and applying a vertical correction with the use of a ballistics program.

2. **Having control of sights**

Sights are the critical bridge between understanding external ballistics, and properly accounting for its effects. If you can predict drop within 0.1" at 1000 yards, it does you no good if you've never verified the actual vertical movement of your scope reticle in response to an adjustment. In the horizontal direction, if you're thinking about spin drift and Coriolis deflection and you're not using a scope level to protect you from the effects of cant, then you're kidding yourself.

3. **Wind Deflection**

Always the wildcard, wind deflection can be the most important or the least important thing on the list on any given day, depending on how it's blowing. Without a doubt, wind deflection is the most critical *non-*

deterministic variable involved in long range shooting. All of the other elements can be measured and accounted for with reasonable certainty. Wind deflection is the final true variable for the long range shooter. Any time and effort spent to hone your wind judging abilities will translate directly into increased success at long range shooting no matter what the discipline.

4. Using an accurate Ballistic Coefficient

The use of an accurate ballistic coefficient is very important for predicting the trajectory of a bullet. Most of the time the advertised G1 BCs are close enough to get you in the ballpark, but if you're serious about the accuracy of your long range firing solutions, you need to make sure that you're using an accurate BC that's based on an appropriate standard (G7 for long range bullets).

5. Accounting for atmospherics

In order to calculate an accurate long range trajectory, you need to measure and account for the effects of air temperature, pressure and humidity. If you don't actually measure the current conditions at your location and calculate a custom firing solution with a portable device, at least generate the drop chart ahead of time for the altitude and expected temperature of where you'll be shooting. The effect of altitude on barometric pressure is very predictable, and you can usually make a good guess on the air temperature based on the season. There is a table in the Appendix (A15) that includes the ambient air temperature and pressure for altitudes up to 10,000 ft.

6. Uphill/Downhill shooting

This is another element that finds its place on the list depending on the situation (like wind). If the inclination angle is small, this may be the least important element of all, but if the inclination is large, the effect is paramount. The primary effect of uphill/downhill shooting is that the component of gravity that pulls directly down from the line of sight is reduced for both uphill and downhill shooting, causing less drop and higher impacts. This primary effect must be accounted for when shooting at long range and at significant angles of inclination. The small component of gravity that works with or against the trajectory is one secondary effect. The other (offsetting) secondary effect is the air density gradient that the bullet encounters on its trajectory. These secondary effects can usually be ignored without consequence because they're offsetting.

7. Gyroscopic (spin) drift

Spin drift is a deterministic variable that can and should be accounted for *IF* all of the higher priority elements are addressed. You shouldn't even start thinking about spin drift if you're not using a sight level and have verified that your reticle tracks perfectly vertical.

8. Coriolis Effect

The Coriolis Effect is by far the least important and subtle element of external ballistics. The effect is deterministic, so it is predictable, but the magnitude is usually so small that it's arguable if it should even be considered at all. If all the other elements have been accounted for (especially the sights), and if the wind is not extremely challenging, and if the circumstances of the shot afford the time, then Coriolis is the last remaining element to consider on very long range shots. Coriolis deflection is always less than spin drift. For shooters in the northern hemisphere, it would be a good idea to use a left twist barrel in order to partially cancel the effects of spin drift and Coriolis.

9. Extended Long Range (ELR) Effects

When a bullet is fired at ranges so long that it slows to transonic speed (close to the speed of sound), there are a host of variables that come into play related to the bullet's flight performance. In particular, the drag of the bullet at transonic speed might not be well modeled by the G1 or G7 standard. The use of custom drag profiles is required to accurately model the drag of a specific bullet at transonic speed if an accurate trajectory prediction is to be made. Furthermore, stability effects at transonic speed can completely or partially compromise the accuracy and predictability of a trajectory. Equipment like optics with 70MOA of elevation adjustments and 1000 yard rangefinders which are perfectly suited for normal long range shooting might be totally inadequate for ELR shooting. The small percentage of shooters who shoot at ELR distances have to overcome these effects, but as long as you're one of the 99% of shooters who work in the supersonic range of the bullet, ELR effects and challenges won't affect you at all.

Part 2: Ballistic Performance Analysis

Chapter 12: Interesting Facts and Trends

This chapter contains some miscellaneous items of interest for long range shooters regarding exterior ballistics. A big part of the reason why there's so much mystery surrounding the subject of ballistics is because everything happens so fast, and very little of what goes on can be directly observed. The sections of this chapter will attempt to bring these subjects into the light and put the mechanics in terms that we're more familiar with. It would be fair to say that there is very little in this chapter that will directly increase your chances of hitting targets. The intent is to sharpen your insight and understanding of what happens during the bullets flight from the rifle to the target. In general, the more basic understanding people have about the fundamental governing principles behind things, the more they will enjoy and master the activity.

Scaling effects

There are some very predictable consequences of scaling bullets up and down thru various calibers. Most of the effects are related to how the weight and area of the bullet are affected by scale. Note that a bullets *weight* is proportional to its *volume*, its *drag* is proportional to its cross-sectional *area* (and form factor), and the *stability* is affected by both *volume* and *area* (and shape). Apparently a clear understanding of *area* and *volume* scaling is worth taking a look at.

As you scale something by a linear dimension, like we're doing with caliber, the *area* of the object goes up with the *square* of the linear change, and the *volume* goes up with the *cube* of the linear scale. For example, consider the square in the top of Figure 12.1. The square is 1 inch on each side, and has an area of 1 square inch. Now double the length of each side (you're scaling it by two). The square is now 2"x2", and has an area of 2^2 inches, or 4 square inches. Furthermore, if our 1" square was a 1"x1"x1" cube (like the bottom of Figure 12.1) and you doubled the length of each side, the cube is now 2^3 inches, or 8 cubic inches in volume. That's a 4 times increase in area, and an 8 times increase in volume from only a 2 times increase of linear scale. Remember that weight is related to volume, meaning that when something grows to 8 times its initial volume, it weighs 8 times its original weight. Bottom line; *weight increases more than area as you scale an object up.* This idea is critical to the understanding of BC for bullets of different calibers.

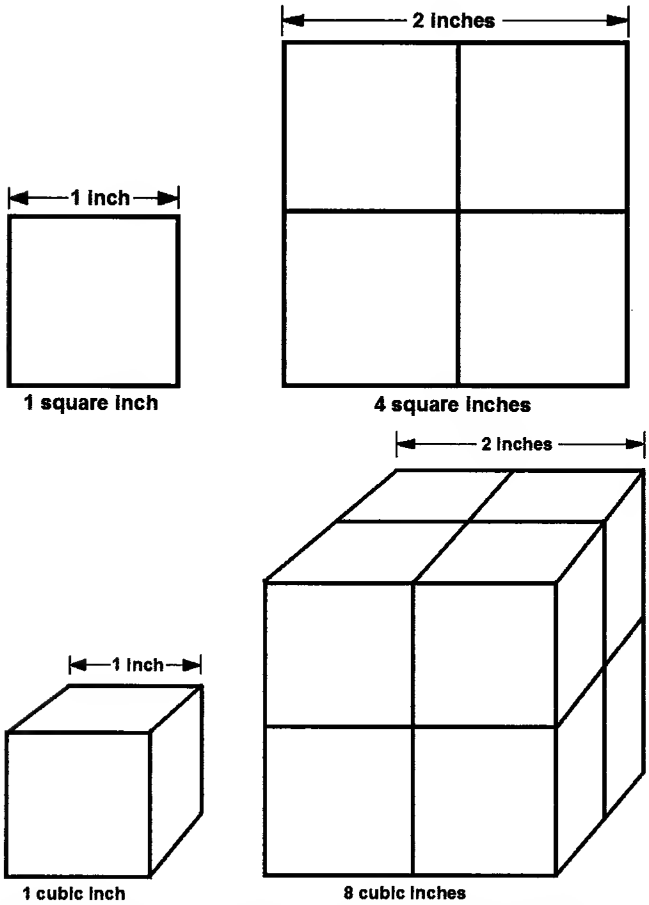
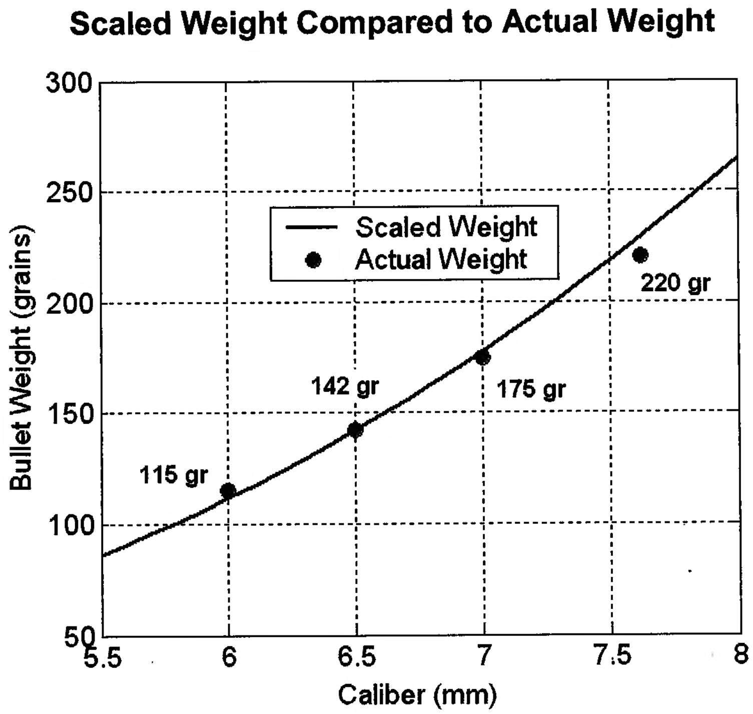


Figure 12.1. Doubling the linear dimension of an object increases the area by 4 times ($2^2=4$) and the volume by 8 times ($2^3=8$).

The difference in linear scale between calibers isn't as cut and dry as simple factors of 2, but the math works the same way. Consider 6.5mm vs 7mm. The linear scale factor going from 6.5mm to 7mm is: 7/6.5 = 1.077. So you can expect the bullet's cross sectional area (which is related to drag and stability) to increase by a factor of 1.077^2, or 1.160. Likewise, you can expect the volume and weight to increase by a factor of 1.077^3, or 1.249. For example, consider the *heavy for caliber* 142 grain 6.5mm bullet. How heavy should a similarly *heavy for caliber* bullet be in 7mm? Just multiply 142 grains by the volume scale factor of 1.249, and you project 177 grains for a *heavy for caliber* 7mm bullet. Sierra's heaviest 7mm bullet is 175 grains and Berger's is 180 grains so you can see how well the scale factor predicts weight.

Figure 12.2 shows how the 6.5mm 142 grain bullet scales from 6mm to .30 caliber. The weights of the actual *heavy for caliber* bullets all fall close to the line of the scaled benchmark 142 grain bullet. Figure 12.2 includes only bullets made by Sierra, but you will observe a similar trend for bullets from other manufacturers as well.

Understanding the consequence of caliber scaling on bullet weight is an important fundamental step in making assessments about ballistic performance of various calibers.



	6mm (.243)	6.5mm (.264)	7mm (.284)	7.62 (.308)
Actual Weight (grains)	115	142	175	220
Scaled Weight (grains)	112	142	177	228

Figure 12.2. Scaling exact proportions of the 6.5mm 142 grain bullet up and down results in calculated weights very close to actual weights for the bullets made by Sierra.

Scaling of the Ballistic Coefficient

Our first exercise with the effects of caliber scaling will be to look at how it affects BC. BC is an easy one because as you can see from the equation below, BC is proportional to mass and area (*cal*^{2} is proportional to area).

$$BC = \frac{bullet\ weight\ /7000}{cal^2 \cdot i}\left(\frac{lb}{in^2}\right)$$

In the above equation, bullet weight is in grains, *cal* is the caliber of the bullet in inches, and i is the *form factor* (review Chapter 2 for a better description of form factor). Basically, the form factor will be the same for bullets *of the same proportions* regardless of caliber, which is convenient for our present analysis. Using the measuredG7 BC of the 6.5mm 142 grain MatchKing (0.301 lb/in^2), the value of the G7 form factor turns out to be i_7=0.968. Using this form factor, you can project the BC for other commonly shaped bullets in different calibers. In doing so, we'll learn something very fundamental about bullet scale and BC.

Notice that in the BC equation, weight (proportional to volume) is in the numerator, and diameter squared (proportional to area) is in the denominator. Earlier we established the scale factor between 6.5mm and 7mm to be 1.077. In order to project the BC of a 7mm bullet based on the BC of a 6.5mm bullet, you multiply the BC by the quotient of scale factor cubed divided by scale factor squared. This is illustrated in Figure 12.3. In simplified terms, you can just multiply the BC by the scale factor itself, as in Figure 12.3

In other words, the BC of similarly shaped bullets scales exactly 1:1 with caliber! For example, the measured G7 BC of the 6.5mm 142 grain MatchKing bullet is 0.301 lb/in^2. Based on that, let's predict the BC of the 7mm bullet. Our scale factor will simply be the ratio of the calibers: 7mm/6.5mm = 1.077, or 0.284/0.264 = 1.077. The math in Figure 12.3 demonstrates that projecting the BC of the 6.5mm 142 grain bullet to 7mm results in a G7 BC of 0.324 lb/in^2.

$$BC = 0.301 \cdot \frac{1.077^3}{1.077^2} = 0.324$$

$$BC = 0.301 \cdot \frac{0.284}{0.264} = 0.324$$

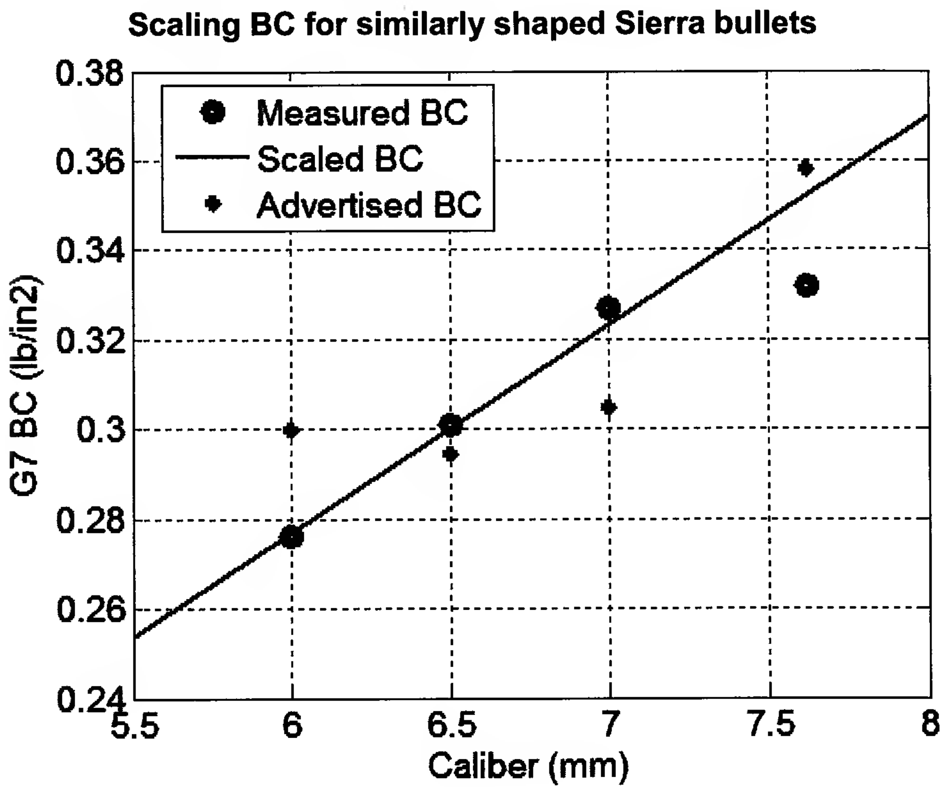
Figure 12.3. Scaling BC.

The actual measured G7 BC for the similarly shaped 7mm 175 grain MatchKing bullet was 0.327 lb/in^2! This compares so well to the scaled value of 0.324 because the profile of the 7mm 175 grain bullet is so similar to the profile of the 6.5mm 142 grain bullet. If you scale the BC of the 6.5mm bullet down to 6mm, you would predict a BC of 0.278 lb/in^2. In fact, a G7 BC of 0.276 lb/in^2 was measured for the 6mm 115 grain bullet! In this way, projecting the G7 BC for different caliber bullets is easy if you know the G7 BC of a similarly shaped reference bullet.

Figure 12.4 shows the results of projecting BC for the range of calibers, based on the 6.5mm 142 grain bullet and the principles of scale. It's very clear that the 6mm, 6.5mm, and 7mm calibers have G7 BC's that fall directly on the trend line, exactly where they're expected based on the scaling analysis. In contrast, the advertised BC's (converted from G1 to G7 referenced) are all over the map. The advertised BC for the 6mm bullet is way higher than it should be considering it has nearly the same profile as the 6.5mm and 7mm bullets (see bullet profiles at the bottom of Figure 12.4).

The 6.5mm SMK has an advertised BC very close to measured. The 7mm SMK has a mysteriously low advertised BC considering it's the same shape as the 6mm and 6.5mm bullets. The 240 grain bullet, although roughly 10 grains heavier than a scaled up 142 grain 6.5mm bullet, has a measured BC lower than the trend line. The reason is clear on inspection of that bullets profile. Clearly the .308 caliber 240 grain MatchKing doesn't share the same shape[18] and low drag form factor as the smaller caliber bullets, and so it's BC falls below the trend line predicted by scaling up those smaller caliber bullets.

I like this exercise because it demonstrates that some things about external ballistics are not as complicated as they seem.



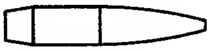
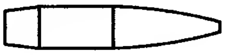
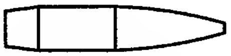
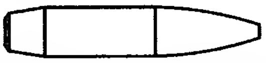
6mm		i7	SD (lb/in^2)	G7 BC (lb/in^2)
115 DTAC		**1.007**	0.278	0.276
6.5mm				
142 SMK		**0.968**	0.291	0.301
7mm				
175 SMK		**0.948**	0.310	0.327
.308 Caliber				
240 SMK		**1.092**	0.361	0.332

Figure 12.4. Notice how blunt the heavy .30 cal bullet is compared to the smaller caliber heavyweights. The relative bluntness of the .30 caliber bullet produces more drag, and hurts the BC.

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[18] In particular the ogive length of the 30 caliber Match Kings is proportionally shorter than the smaller caliber Match Kings.

Consider the plot in Figure 12.4 with the advertised BC's all over the map. One might (understandably) wonder why the advertised BC of the 175 grain 7mm MatchKing is only slightly higher than a much smaller 115 grain 6mm DTAC bullet. Of course there's the problem of velocity dependence of the G1 BC which allows for some confusing, but not necessarily *false* claims. The situation with the super high *claimed* BC of the 6mm bullet can cause people to make huge decisions based on performance they *think* is there. However in the end, there's really nothing supernatural going on after all. The same thing goes for the 7mm. Who would choose to shoot a 7mm bullet with all the extra recoil when the *advertised* BC's don't indicate a real advantage over the 6mm or 6.5mm? It should be comforting to know that all 3 bullets in all 3 calibers with the same shape do actually have performance that scales as the laws of nature dictate. The one outlier in the group is the .308 caliber 240 grain MatchKing. Despite being 10 grains heavier than a scaled up 142 grain 6.5mm bullet, it has a BC far below the trend line. As previously stated, the reason is obvious if you look at the relative bluntness of that bullets profile, and its correspondingly poor G7 form factor.

The bottom line is when you actually measure the Ballistic Coefficient and reference it to a proper (non-velocity dependent) standard; *so many things clear up and are consistent with common sense!* With the historical potential of unreliable advertised BC's referenced to the inappropriate G1 standard, it's no wonder why BC has been so much of a mystery. I hope that this book can succeed in conveying the fact that *real* BC's are useful and not difficult to understand.

Of course in the end, the bullet is the same. Its performance is its performance, no matter how you choose to quantify it. *It simply makes it easier to gain an accurate understanding of the bullets performance if you're using accurately measured and properly referenced BC's.*

Hitting targets at long range has a lot to do with the decisions you make about your equipment, which are based on your assessment of ballistic performance. The more accurate your understanding of the bullets performance is, the better informed your decisions will be, and the more success you will have at long range shooting. Basing important ballistic assessments on the sloppy G1 BC's that are advertised by the bullet makers has historically been a very weak link in the kill chain for long range shooters, both in their ability to assess the relative performance of various bullets/calibers, and their ability to calculate accurate trajectories for their chosen system.

Inherent BC Advantage of the Larger Calibers

Our scaling exercise has demonstrated that for similarly shaped bullets that are proportional in weight for their caliber, BC increases with caliber by a 1:1 ratio. It should be no surprise that larger caliber bullets can have higher BC's. We now have the fundamental knowledge of how and why it's so.

Knowing that larger caliber bullets have higher BC's isn't enough information to make a complete performance assessment. You can't simply assume that you can drive bullets of all calibers to the same speeds. In general, it's harder to get the large caliber bullets to the same high muzzle velocities that are possible with smaller calibers. Be careful to consider realistic muzzle velocities along with BC when you're comparing ballistic performance across calibers. There will be some more detailed analysis of BC and muzzle velocity effects on performance in a later chapter.

I've made a big deal out of BC so far. However, before we leave the subject, I'd like to make an important point. BC's by themselves don't kill targets or win matches! Let's consider a long range rifle match. You can't show up at a match with what you believe to be a superior ballistic combination of caliber and bullet, and expect your equipment to win for you. The difference in ballistic performance among the rifles at any given match is usually quite small. Only a small margin separates the best from the worst ballistic performer. Your ability to effectively read the wind and properly adapt to its subtle changes is far more important than a few points of BC. However, high BC is still important.

Consider the following situation. Two competitors shoot a match against each other in the same conditions. Shooter A has a small ballistic advantage over shooter B. If both shooters are equally skilled at reading the wind, shooter A stands a *slightly* better chance of winning that match, though either shooter could win any given match. If these two shot 20 matches against each other, Shooter A is almost certain to produce a *higher **average** score* (or smaller average group) than shooter B.

Effects of Scaling on Gyroscopic Stability

Much of the current discussion on stability is a review of the material presented in Chapter 10. It's reintroduced here as necessary in order to demonstrate the consequence of scale on stability.

The gyroscopic stability factor (SG) is a measure of how well a bullet is stabilized. In *theory*, SG only needs to be greater than 1.0 at the muzzle in order to be stable (not tumble) in flight. In *practice*, bullets should have an SG of at least 1.5 in standard atmospheric conditions to allow for a margin of error.

Two basic things contribute to the gyroscopic stability of spinning bullets: 1. *Aerodynamic overturning torque* acts to de-stabilize the bullet, and 2. *Inertial effects of the spinning mass* stabilize it. As long as the stabilizing effects are stronger than the de-stabilizing effects, the bullet flies point first.

The destabilizing aerodynamic effects are related more to the *area* of the bullet, whereas the stabilizing effects are related more to the *weight* of the bullet. Does this sound familiar at all? It's the same logic involved in the scaling of the BC. *Increasing the linear scale of the bullet effectively generates more stabilizing mass (inertia) than destabilizing aerodynamic* *torque.* The net result is that the larger caliber bullet, fired at the same speed and rate of twist is more stable. In other words, larger caliber bullets tend to have slower twist requirements to achieve stability compared to smaller calibers.

Another way to look at twist rate is that a given class of bullet will require a constant *calibers per turn* of twist rate.

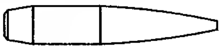
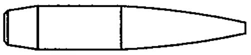
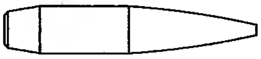
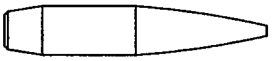
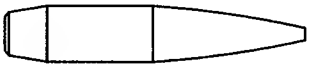
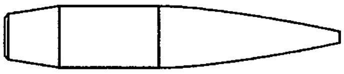
Bullet Description		***Inches* per turn**	***Calibers* per turn**
.224 cal 90 grain		1:7"	31
.244 cal 115 grain		1:8"	30
.264 cal 140 grain		1:8.5"	32
.284 cal 180 grain		1:9"	32
.308 cal 230 grain		1:10"	33
.338 cal 300 grain		1:10"	30

Table 12.1. Note that the required *inches per turn* systematically increases as the caliber grows indicating slower twist. However the *calibers per turn* is relatively constant at ~31 calibers per turn.

Refer to Table 12.1 to see what I'm talking about. Notice that the *heavy for caliber* bullets from .224 thru .338 all require about the same 31 calibers per turn, even though this translates to very different twist rates in terms of *inches per turn.*

One last point regarding stability: Starting as soon as the bullet leaves the barrel, SG begins to increase. The reason is simply because the forward motion of the bullet is decreasing much faster than the rotational speed of the bullet. In other words, *de-stabilizing effects are eroding quicker than stabilizing effects.* The result is that SG grows as the bullet goes downrange.

Remember there is an entire chapter in Part 1 of this book that deals with gyroscopic and dynamic stability in greater detail. This brief encounter with the subject is here to highlight the effects of scale on stability.

The Energy of Ballistics

In any scientific investigation of the governing physics behind things, a study of the energy balance involved is usually quite enlightening. In this section, we'll use a basic energy analysis to discover some interesting facts about a bullets flight.

First let's talk about how to quantify a bullet's kinetic energy. Kinetic Energy (KE) is a bullet's energy of motion. It's measured in foot-pounds (ftlbs). Think of it this way, if a bullet were fired straight up with 100 ft-lb of KE and it impacted a weight of 1 pound, the weight would be driven 100 feet up. If the same bullet were fired against a 100 pound weight, the weight would rise up 1 foot. KE is commonly used to quantify a bullets striking energy, and can be calculated with the following equation.

$$KE = \frac{BW \cdot V^2}{450800}$$

Equation 12.1

Where:
KE = Kinetic energy at the muzzle in foot-pounds
BW = bullet weight in grains
V = Velocity in feet per second

It's a well-known fact that a bullet slows down as it flies thru the air. The bullet has some velocity at the muzzle, and a corresponding amount of kinetic energy. As the bullet flies downrange, it slows down, and the amount of energy possessed by the bullet is depleted. *Where does the energy go?* The law of conservation of energy dictates that the energy lost by the bullet has to go somewhere. It can't just disappear. In the case of a bullet, the energy of its forward motion is lost to the *sound and heat* that the bullet transmits to the air as it flies downrange. It might be hard to imagine so much energy being converted into sound and heat, but it's an exact *one-for-one* trade the bullet makes with its kinetic energy. To put the energy into familiar terms, consider a .308 caliber 175 grain bullet fired at a muzzle velocity of 3000 fps. At the instant the bullet emerges from the rifle barrel, it possesses exactly 3494 ft-lb of energy. Think of this energy as the bullets *budget*. In order to maximize external ballistic performance, the bullet must get to its target as efficiently as possible which means it has to be *frugal* when spending its energy. If the bullet is very streamlined, and has a low drag form factor of around 0.95, then it will reach a target at 1000 yards at 1,510 fps, which is just over ½ of its original speed; and 885 ft-lb which is just over ¼ of its original energy (remember that kinetic energy is proportional to velocity squared). In this example, the bullet *spent* 2,609 ft-lb of energy getting to the target. In other words, even though the bullet has a low drag profile, it still managed to lose 2,609 ft-lb of energy to the atmosphere. Since the bullets flight is supersonic, most of this energy was used to continuously compress the air into a shockwave which is difficult and noisy work. The bullet managed to dump this 2,609 ft-lb of energy to the atmosphere during a flight which lasted 1.41 seconds. In other words, the bullet lost 1,850 ft-lb of energy per second during its flight on average. When you talk about the rate of energy expenditure, you're talking about *power*. 1,850 ft-lb per second is equivalent to 3.36 *horsepower*. In electrical units, that's 2,509 *Watts*. Remember this is the average rate of energy transfer for 1000 yards. During the first 100 yards, the rate is much greater, and it's much less during the last 100 yards. For the first 100 yards, the bullet loses 391 ft-lb in 0.103 seconds, which is an energy transfer rate of 6.9 horsepower, or 5,149 Watts. During the last 100 yards, the bullet loses 154 ft-lb in 0.1908 seconds, which is an energy transfer rate of 1.47 horsepower, or 1,094 Watts. So from the muzzle to 100 yards, the bullet is losing energy at a rate that could comfortably light up over 51 100 Watt light bulbs at once. Between 900 and 1000 yards, the bullet could light up almost 11 100 Watt light bulbs at the rate its loosing energy. For shooters who have spent any time downrange listening to bullets fly overhead (as in the target pits of a rifle match), the energy being lost by the bullet is evident as a very loud *crack*, which is the bullets own little *sonic boom.*

Consider another 175 grain 30 caliber bullet fired at the same muzzle velocity, but this bullet has a higher drag profile, and a form factor of 1.05. This bullet will experience 10% more drag than the previous bullet which had a form factor of 0.95. As a result, the higher drag bullet will lose velocity and energy at a greater rate than the low drag bullet. You could say the high drag bullet is not a smart spender of its energy. He's going downrange wasting energy on making an impressive and expensive shock wave, all the time losing velocity and energy like there's no tomorrow. The cost of inefficient high drag flight has a negative impact on ballistic performance. Every measure of ballistic merit is degraded for a higher drag bullet compared to a lower drag bullet.

Most of the energy possessed by a bullet is in the form of translational, or linear kinetic energy, but not all of it. The bullet also stores some energy as *rotational* kinetic energy. At the muzzle, a typical .30 caliber bullet will possess about 8-10 ft-lb of rotational kinetic energy. Since the spin of the bullet is not directly opposed by aerodynamic drag, the bullet is able to maintain its rotational speed and energy better, but it does decay over time. At a distance of 800 yards, the bullet will have slowed to a rotational speed corresponding to roughly 5 or 6 ft-lb. This rate of energy loss is only equal to about 4.5 Watts. This is about the amount of power required to operate a small desk radio.

It's best for the bullet's external ballistic performance if it's able to maintain as much energy as possible on its way to the target. Furthermore, in some shooting objectives (hunting), the bullet has to *cash in* whatever kinetic energy it has remaining by depositing it into the target in the most lethal fashion. This *most lethal fashion* is what comprises the subject of terminal ballistics, but we'll take a quick look at the bullets terminal performance from an energy perspective.

A bullet is able to cause the death/incapacitation of an animal with two primary mechanisms. The first is the obvious penetration/laceration of the animal's vital organs which kill the animal by depriving its brain of oxygen. This is how arrows and knives kill. The high speed bullet has another very powerful mechanism that it kills with, which is *hydrostatic shock.* When a bullet traveling at supersonic speed enters a medium (animal) that's composed primarily of incompressible fluid and tissue, a very strong shockwave is propagated thru the animal. In the vicinity of the bullets path, the shock will be violent enough to actually damage tissue, even though no part of the bullet has physically touched it. If the shock is strong enough, it can also affect the animal's brain, causing immediate incapacitation and/or unconsciousness. The strength of the shock is proportional to the speed of the bullet, and how much the bullet expands. The two ends of the terminal performance spectrum are:

- Maximum penetration – minimum expansion. Bullets having solid construction are at this end of the spectrum. The good part about bullets that don't expand is that you can count on them to *cash in* all of their energy in the form of penetration, getting deep into the vitals of a thick animal. The downside is, the bullet may very well pass completely thru the animal and exit with sufficient velocity/energy. The energy possessed by the bullet as it exits the animal is *wasted* energy because it could have been used to cause more shock and damage if it had expanded more.
- Maximum expansion – minimum penetration. Bullets at this end of the spectrum will expand rapidly on impact, break up and exert all of their energy in one powerful shock. The downside is if the animal is large, the bullet may not have penetrated into the vitals, and wasted all its energy just under the animal's skin.

The best way for a bullet to manage its energy on impact is a balance between penetration and expansion. The challenge of designing a bullet for *optimal* terminal performance is that there is such a wide range of animal sizes and impact velocities that the bullet has to work with. If the bullet were *specifically designed* to optimize its energy delivery on small thin skinned game at close range, that bullet will not be very effective on large, thick skinned game at long range. Terminal ballistics forces severe compromises on bullet construction. From an energy point of view, the goal is to have enough penetration to get the bullet into the animal's vitals, and then spend the rest of its energy creating an effective wound channel by creating a strong hydrostatic shock which can instantly incapacitate the animal.

Twist rate effect on muzzle velocity

This topic is outside the scope of this book, but is related to energy so I'll briefly share my thoughts here. A belief that's commonly held is that a barrel with a faster twist rate will produce a lower muzzle velocity, all else being equal. The reasoning is that the additional energy that's required to spin the bullet faster robs the bullet of some amount of forward velocity.

Assuming that a given charge of powder contains enough energy to propel a .30 caliber 175 grain bullet at 2800 fps from a 1:12" twist barrel, how much velocity loss can we expect if the same bullet is fired from a 1:10" twist barrel with the same powder charge?

Well, in the 1:12" twist barrel, the bullet will have about 3046 ft-lb of translational KE, and about 9 ft-lb of rotational KE, for a total of 3055 ft-lb KE delivered to the bullet. If the twist rate were 1:10", the rotational KE would increase to 10.8 ft-lb, leaving only 3044.2 ft-lb of translational KE, which corresponds to a muzzle velocity of 2799 fps.

This energy balance indicates that twist rate has a negligible effect on muzzle velocity. However there's more to consider about the internal ballistics affecting this scenario. For example, the assumption that the powder delivers the same amount of energy to the bullet is probably not valid. Burning powder produces pressure that is proportional to its temperature and pressure. The faster rifling twist rate might increase the pressure level enough to cause the powder to produce more pressure than a slower twist barrel. It might even be possible that a faster twist might produce equal or greater muzzle velocity due to the effects on the powder burning.

Another thing to consider is variations in the internal finish of a barrel, regardless of spin rate, that will affect the muzzle velocity.

In conclusion, I don't think there's a practical correlation between slower twist rates and achievable muzzle velocity.

The nature of bullet dispersion

A common belief by many shooters is that some rifles will shoot better *angular* groups at long range as compared to short range. For example, a rifle that can group no better than 1-inch at 100 yards (1 MOA) can routinely shoot 1-inch groups at 200 yards (1/2 MOA). This topic has been hotly debated in various internet forums and ranges for many years.

The theory for how *angular convergence* is possible is most commonly related to the bullets *going to sleep.* It is argued that the bullets fly a corkscrew flight path early in the flight, which prevents the bullets from shooting good groups at 100 yards. Then, as the bullets stabilize and *go to sleep,* the flight path straightens out and groups tighten up at longer ranges.

I've been able to model these flight dynamics using the 6 Degree Of Freedom (6-DOF) trajectory model. The *corkscrew* flight path does exist for bullets that are flying with pitch and yaw. The technical term for this flight dynamic is *epicyclic swerve.* In reality, the magnitude of the epicyclic swerve is very minimal; amounting to about one tenth of one caliber; so like 0.030" for a .308 caliber bullet. This is not enough to explain the observation of bullets shooting 1-inch groups at 100 yards and 1-inch groups at 200.

The idea of converging flight paths was put directly to the test when I built the *shoot thru target* at the Applied Ballistics Laboratory. The shoot thru target is a frame that supports a thin paper at 100 yards, which the bullets pass thru on their way to 300 yards where they print another group. Shooting groups of different bullets from various rifles allows for a direct screening of the dispersion that happens between the two ranges.

Many combinations of rifles and bullets were tried, but none demonstrated dispersion that wasn't linear; meaning if the group was 0.5" at

100 yards, it would be very close to 1.5" at 300 yards. Minor variations occurred due to wind and muzzle velocity variation but nothing ever demonstrated a systematic angular convergence.

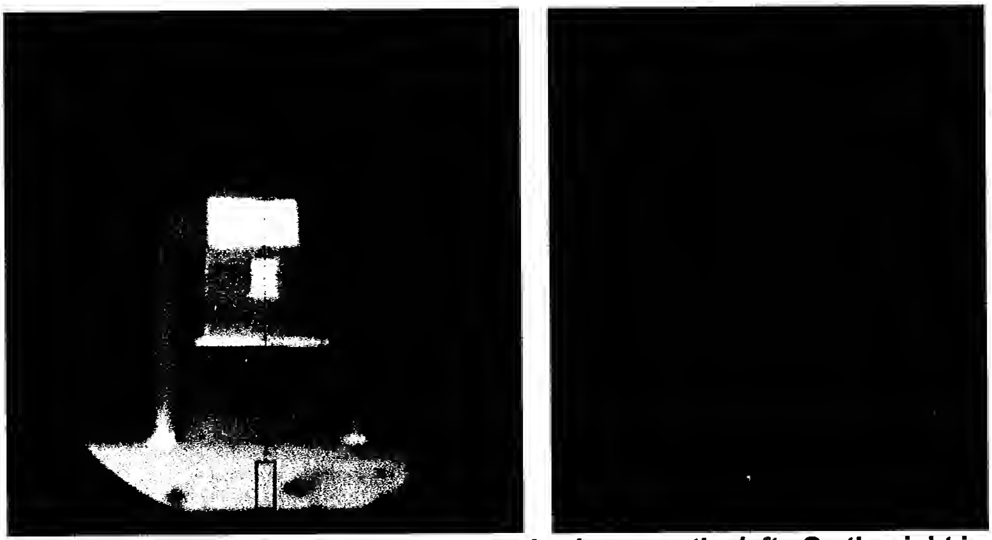


Figure 12.5. The shoot thru target set up is shown on the left. On the right is a sample group showing how the group printed at 100 yards (top) and how it looked at 300 yards.

For those interested in more details and explanation of the shoot thru target results, you can read about it in *Modern Advancements in Long Range Shooting – Volume 2.* All of the live fire testing done on the shoot thru targets is published in that book, along with theories as to how and why dispersion works related to bullet stability.

Chapter 13: Example Performance Analysis

This chapter is going to present a typical performance analysis between two bullets as an example. The objective of the performance analysis is to determine which of two bullets is *better* for a specific application. For the purposes of presenting an example, the application of long range prone shooting was chosen. The question that the performance analysis aims to answer is: which bullet is *better* for long range prone shooting: the Berger 168 grain VLD or the 180 grain VLD, and why? The analysis focuses on the trade-off between weight and muzzle velocity, and uses wind deflection as the main measure of ballistic performance in deciding which is *better.* Although this analysis uses these particular bullets as an example, the principles of the performance analysis can be applied to any bullets under investigation. At some points in this chapter the discussion will stray off topic. This is done deliberately to reinforce some of the elements presented in Part 1 of this book.

Introduction

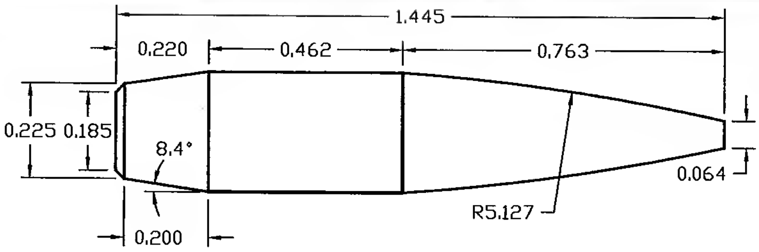
Berger currently offers two bullets in 7mm: 168 grain and 180 grain VLD's. The low drag profiles of these bullets make them very attractive options for long range shooting. The versatility of these two bullets extends from big game hunting to tactical shooting, to long range Benchrest competition and everything in between including long range NRA prone and F-class score shooting. This analysis will begin by presenting the ballistic properties and measured performance of these two bullets in a general sense, meaning the information applies to all types of shooting that these bullets might be used for. Later in the analysis, we'll compare the ballistic performance of the two bullets for the specific application of long range NRA prone slow fire competition.

Design of the Bullets

Figures 13.1 and 13.2 show dimensioned drawings of the bullets under consideration in the present analysis, along with their measured drag and BC data.

Note the very aggressive secant ogive profile of the VLD design. This design feature represents a compromise that many shooters know all too well. The long radius secant ogive is great for drag reduction; however, the grouping potential of VLD bullets is known to be very sensitive to seating depth. Shooters who wish to take advantage of the low drag VLD bullets have to take care when establishing the seating depth of these bullets.

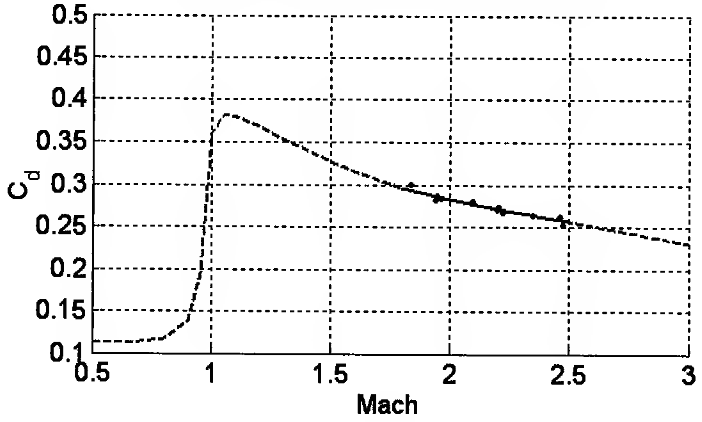
Berger .284 caliber 168 grain VLD



Dimensions taken from Lot#899

Sample Size:	**5**	**Ogive Radius:18.05**	**calibers**
Sectional Density:	**0.298 lb/in²**	**Rt/R:**	**0.57**

Drag and Ballistic Coefficient



fps / Mach	C_d	i_7	BC_{G7}	i_1	BC_{G1}
1500 / 1.34	0.335	0.914	0.326	0.508	0.586
2000 / 1.79	0.297	0.946	0.314	0.476	0.625
2500 / 2.23	0.270	0.948	0.314	0.476	0.625
3000 / 2.68	0.249	0.959	0.310	0.470	0.633
	Average:	**0.942**	**0.316**	**0.483**	**0.617**
	Variation:	**0.046**	**0.015**	**0.038**	**0.047**

Figure 13.1. Measured drag and BC of the Berger 168 grain VLD

When viewed side by side, it's clear that the boat-tail and ogive of the two bullets are very similar. The only design difference between them is the length of the bearing surface. The bearing surface of the 180 grain bullet is 0.079" longer than the 168 grain bullet, and the overall length is 0.080" longer. Some minor differences are apparent from the drawings. For example, there is a 0.7 degree difference in boat-tail angle, a 0.001" difference in ogive length, a 0.4 caliber difference in ogive radius, and a 0.005" difference in meplat diameter. It's important to point out that the dimensions on these drawings come from my measurements of the given lot numbers. The measurements are made on a lathe with a dial indicator, and I don't claim that they're perfect. The uncertainty of the dimensions in the drawings is not important to the performance assessment of the bullets, I only bring it up to clarify that my measurement of BC is tied to this particular lot number, with these nominal dimensions.

The property that's most likely to vary for different lots of bullets is the meplat diameter (true of any brand). Near the end of the article is a table showing how you can expect the BC to vary for different meplat diameters. My test results are valid for the meplat diameter shown in the drawings, which is the average value for the lot tested.

The observation that both of these bullets have similar ogive and boat-tail designs indicates that they should have similar form factors. They have different length bearing surfaces, but *of all the parameters of bullet design, the bearing surface length has the least influence on form factor.*

The three major components of aerodynamic drag on a bullet are: (shock) wave drag, base drag, and skin friction drag. Wave drag makes up most of the drag, and is affected most by the ogive length and shape, including meplat diameter. Base drag is the second most important component of drag and can be reduced with a properly designed boat-tail. Skin friction drag is the least important component of drag, and is proportional to the wetted area of the bullet. The differences between the two bullets that would affect the form factor the most are the meplat diameter and bearing surface length. The form factor of the longer 180 grain bullet is improved by having a smaller meplat diameter than the 168 grain bullet[19], but the added length increases the wetted area and skin friction drag. The offsetting effects result in very similar form factors for the two bullets.

Interpreting the Measured Test Data

The 180 grain VLD is the bullet that I personally shoot in competition (long range prone), so it's been tested more than the lighter 168 grain VLD. I've got data for 17 shots of the 180 grain VLD, and 5 shots for the 168 grain VLD. If the data is clean, 5 shots are typically all that's required to determine the BC with very good accuracy. The number of shots used to determine drag and BC is given as the *sample size* below the dimensioned drawings in Figures 13.1 and 13.2. You can also get an idea for the amount and consistency of the data by looking at the experimental points on the drag curve, which is the bottom graphic in Figures 13.1 and 13.2. Even though there were only 5 shots for the 168 grain VLD, there is very little scatter in the measured data which is an indication that the measured BC is reliable. The 180 grain VLD was tested on two separate dates, 3 months apart. The first test included samples with the meplat trimmed, unmodified, and pointed. The data from the two test dates for the unmodified meplat is shown together in Figure 13.2, and agree within 1%.

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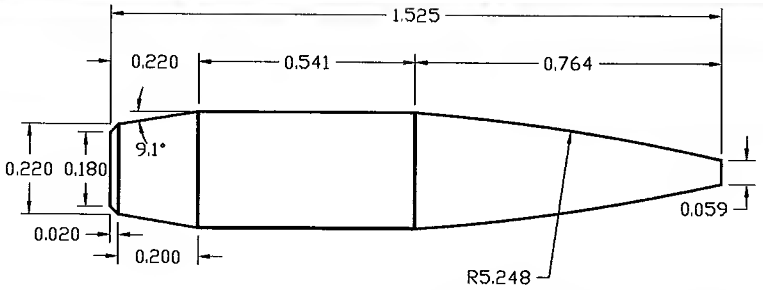
[19] This is not by design; it's a consequence of manufacturing tolerances.

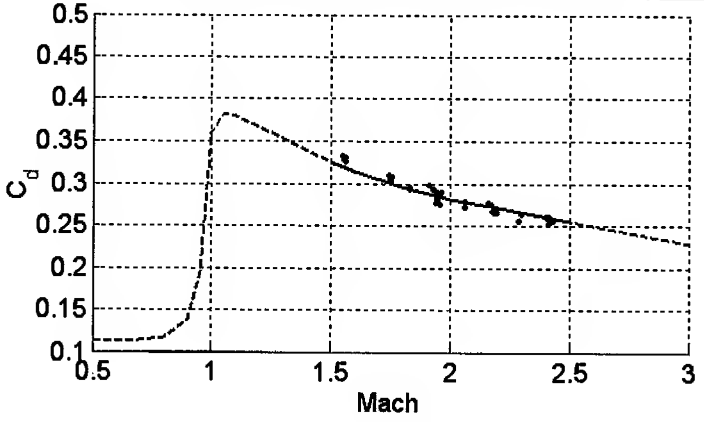
Berger .284 caliber 180 grain VLD



Dimensions taken from Lot#508

Sample Size:	**17**	**Ogive Radius: 18.48 calibers**
Sectional Density:	**0.319 lb/in²**	**Rt/R: 0.54**

Drag and Ballistic Coefficient



fps / Mach	C_d	i_7	BC_{G7}	i_1	BC_{G1}
1500 / 1.34	0.355	0.967	0.330	0.538	0.593
2000 / 1.79	0.301	0.962	0.331	0.484	0.659
2500 / 2.23	0.266	0.934	0.341	0.469	0.679
3000 / 2.68	0.239	0.921	0.346	0.451	0.706
	Average:	**0.946**	**0.337**	**0.486**	**0.659**
	Variation:	**0.047**	**0.017**	**0.086**	**0.113**

Figure 13.2. Measured drag and BC of the Berger 180 grain VLD

Since the ogive design of the two bullets is the same, the effects of meplat trimming and pointing on the form factor of the 180 grain VLD apply equally for the 168 grain VLD. Because of that fact, we can know the effects of modifying the meplat on the BC of the 168 grain VLD.

The solid black portion of the drag curve in Figures13.1 and 13.2 is the velocity range over which the drag was actually measured. The gray dotted line shows how the G7 drag profile is projected on either side of the measured data.

According to the numbers in Figure 13.1 for the 168 VLD, it appears that there is more variation of the G7 form factor (i_7) than the G1 form factor (i_1). Actually, the G7 *percentage* variation is less than the G1 *percentage* variation (4.9% variation for G7 vs. 7.9% for G1) meaning that the G7 standard is a better fit for this bullet than the G1 standard. For the 180 grain VLD there is more data over a wider range of velocity which allows a more accurate description of the drag curve and BC variation. As a result, there is much less variation for the G7 form factor and BC than G1. In reality, the variation in G7 form factor for the 168 VLD is probably closer to what's shown for the 180, but it's not as evident in the data because only 5 shots were used and they don't span as much velocity as the data for the 180 VLD.

It is worth mentioning that a G7 form factor below 0.95 is considered very low. These VLD's, the Sierra 175 MatchKing, and Hornady 162 grain Amax are 4 heavyweight bullets in 7mm that have G7 form factors below 0.95. This availability of heavy low drag bullets in 7mm makes it a great caliber for long range shooting. In 6.5mm there are 3 bullets with G7 form factors below 0.95, and a handful right around 0.96. In .243caliber, there are only 2 bullets below a G7 form factor of 0.95. In .308 caliber, none of the bullets tested have a G7 form factor less than 0.95. The closest is the 208 grain Hornady Amax at 0.967. I think this lack of low drag .30 caliber bullets has played a role in that caliber falling out of popularity in favor of the smaller calibers in recent years.

In a previous section, we discussed the similarities in design between these two bullets, and suspected that the measured form factors would be very similar. You can see from Figures 13.1 and 13.2 that the measured form factors are indeed very close: 0.942 compared to 0.946. This match appears more impressive than it is, because my measurements aren't that precise! A more honest way to report the measured form factors is: 0.942 (+/-0.01) compared to 0.946 (+/-0.01). In light of the measurement uncertainty of +/-1%, we can say that these two bullets have, for all practical purposes, the *same* form factor as expected from the design.

Since the form factors are the same, the difference in BC between these two bullets is entirely due to the greater weight of the heavier one. Remember the equation for BC:

$$BC = \frac{bullet\ \ weight\ /7000}{cal^2 \cdot i}\left(\frac{lb}{in^2}\right)$$

Where:
bullet weight = bullet weight in grains
cal = bullet caliber in inches
i = form factor (G1 or G7)

Using the G7 form factor of 0.942 for the 168 grain VLD yields a G7 BC of 0.316 lb/in^2. We can project the BC of the heavier bullet by simply multiplying the G7 BC of the lighter bullet by the ratio of weights, like this: 0.316 (lb/in^2) * 180/168 = 0.339 lb/in^2. Using the actual measured form factor of the 180 grain VLD yields a G7 BC of 0.337 lb/in^2, which agrees well with the scaled prediction.

Understanding the components of BC can be a powerful piece of knowledge. BC has traditionally been considered a mysterious and controversial number, but when it's used right, and referenced to the proper standard (G7 for long range bullets) it's really quite simple and predictable.

For example, as shown above, the BC is calculated using sectional density and form factor. The sectional density is easy to figure, it's just the bullet weight (in pounds) divided by the caliber (in inches) squared. Now, to get BC, you just need the form factor. Form factors referenced to the G1 standard are not very intuitive for long range bullets, and they vary a lot with bullet velocity. But using the G7 standard, form factors range from as low as about 0.94 up to about 1.12, and it doesn't change with velocity. A bullet with the profile of the .30 caliber 155 grain Lapua Scenar has a form factor very close to 1.0 because that bullet is shaped very similar to the G7 standard projectile. Bullets that are more streamlined have a lower form factor, and vice-versa, but the range is pretty narrow; from 0.94 for very streamlined bullets to 1.12 for non-streamlined bullets. Given the above information and a hand calculator, you can actually *guess* at the form factor just by looking at a bullet's profile, and calculate a G7 BC that's possibly more accurate than the manufacturers advertised number! More and more modern ballistics programs are offering the option to input BC's referenced to multiple standards including G1 and G7. However, for long range bullets, G7 is always the better option. After careful inspection of the data presented in the book: *Ballistic Performance of Rifle Bullets*, you will have a pretty good understanding of the relation between bullet shape and G7 form factor.

Meplat (bullet tip) modifications

Effects of both meplat trimming and meplat pointing were tested for these bullets. For those not familiar with these procedures, here's a quick explanation. Meplat trimming is the process of cutting the ragged bullet tips to a smooth, uniform diameter. The objective is to eliminate bullet to bullet variations in BC that are due to inconsistent tips. The downside to meplat trimming is that it leaves the bullet tips slightly larger, which decreases the average BC a little. Meplat pointing is a treatment whereby the bullet is pressed into a die that has an insert at the top that squeezes the bullet tip down in diameter. In this way, a large meplat can be made smaller. The net result is an increased and a more uniform BC. Table 13.1 shows the effects of trimming and pointing the meplat on the G7 BC of the two Berger bullets.

	168 grain VLD		**180 grain VLD**	
	Meplat	**BC_{G7} (lb/in^2)**	**Meplat**	**BC_{G7} (lb/in^2)**
Trimmed[20]	0.084"	0.309	0.097"	0.324
Nominal	0.068"	0.315	**0.062"**	**0.336**
	0.064"	**0.316**	**0.059"**	**0.337**
	0.060"	0.317	0.055"	0.338
Pointed	0.044"	0.323	**0.039"**	**0.344**

Table 13.1. Effects of trimming and pointing meplat. Numbers in Bold indicate meplat sizes that were actually tested.

Up to this point we have been taking a close look at the bullets under consideration. We have a good idea of the BC's of these bullets, and what to expect from meplat modifications like trimming and pointing. With this fundamental data established, we'll now get into the real performance analysis. All of the steps taken so far in the analysis apply universally regardless of the shooting application. At this point, the analysis will focus on the specific application of long range (1000 yard) NRA slow fire prone competition. If your application were different, the steps you would take to assess the performance of the bullets would be different. For example if you were comparing these bullets for a hunting application, kinetic energy would be a very important consideration. However in the present analysis, KE is irrelevant.

What is the Key Measure of Ballistic Performance for this Application?

There are many measures of ballistic performance to consider that depend on the application. *The most important part of a ballistic performance analysis is identifying what's most important for the intended application.* One common mistake is to think that a flat trajectory is a universally important measure of merit in shooting. Shooters will brag about how little their bullets rise above the line of sight on their way to the target. I'll sit down behind them to score and they say "watch how flat these suckers shoot", as if a flat trajectory alone is worth points. Well my hearing has been dropping off, but I've never heard any limbo music at a rifle match! You don't get any awards for keeping your bullets under a certain height on their way to the target. Granted, a flat trajectory can be a symptom of good ballistic performance, but it's not important by itself for target shooting at known distances. If you focus on the wrong performance measures for your application, you can end up making poor decisions about your equipment. Make sure you know what measures are really important for your intended application and focus on them.

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[20] This represents an extreme amount of trimming. The large value is given to bound all possibilities, and to show the consequences of excessive trimming.

I hasten to point out that there are other relevant factors for long range target shooting outside the realm of exterior ballistics. Consider for example, the grouping potential of the bullet. This is a combination of quality control for the bullet, as well as bullet/barrel alignment, reloading practices, etc. The bullet you choose to shoot at long range is a compromise of many factors including recoil, barrel wear, precision, etc. *The current focus is only on the exterior ballistic performance of these bullets, and is only one of many things to consider when choosing a bullet.* There are many things that have to be done right at the reloading bench, in developing a shooting position, mental management, wind reading, etc. to be successful in long range competition shooting. This book isn't intended to cover all of those subjects, just the external ballistic performance.

At the highest levels of NRA Long Range prone shooting, given *no wind* conditions, most of the top shooters are able to clean (200/200) the long range target. *When the wind blows, points begin to drop.* The winners are the shooters who best manage the challenges presented by the wind, and drop the *fewest* points. There are many things involved in *managing the wind.* The most important thing is the ability to judge the effects of the wind, and apply accurate corrections. Choosing equipment that has superior ballistics is a way to *lighten the load* on the task of shooting in the wind. No bullet, no matter how high the BC, will make it easy to shoot high scores in tricky winds. But choosing equipment with strong ballistics can give you a slightly greater margin for error, and that might be enough to make the critical difference.

Slow and Heavy versus Light and Fast

The two bullets under investigation exemplify a classic ballistic comparison. *Will the extra speed of the lighter 168 grain VLD make up for its lower BC in terms of wind drift?* This question was investigated generically in the earlier chapter on wind drift. The key part to focus on is *how much* extra speed will the lighter bullet have? To be fair, we will assume an equal level of muzzle *energy* for the two bullets, which implies equal chamber pressures for both. Note: this is NOT the same as using the same powder charge for both bullets. For this case study, I'll assume moderate pressure levels for a medium volume 7mm chambering: the .284 Winchester. The .284 Winchester can comfortably propel the 180 grain VLD to 2800 fps in a 28" to 30" barrel. Given the same chamber pressure and kinetic energy at the muzzle (3130 ft-lb), the 168 grain VLD would achieve a velocity of 2898 fps, call it 2900 fps. Using these numbers, we can make a fair apples-to-apples comparison between the two bullets.

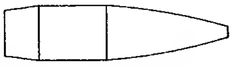
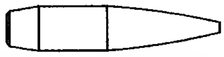
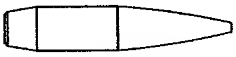
Bullet	Velocity (fps)	i7	G7 BC (lb/in^2)	Wind Drift
 *30 cal 155 grain Scenar*	3000	0.988	0.236	93.3”
 *7mm 168 grain VLD*	2900	0.942	0.316	64.2”
 *7mm 180 grain VLD*	2800	0.946	0.337	62.3”

Table 13.2. Wind drift is for a 10 mph direct crosswind at 1000 yards in standard atmospheric conditions.

Obviously, if we assumed equal velocities for both bullets, the heavier, higher BC bullet would win hands down but it wouldn’t be a fair comparison. *You simply can’t achieve the same velocity with a heavy bullet that you can with a lighter bullet with the SAME pressure and barrel length.* Performing the comparison with equal muzzle *velocities* (as is commonly done) wouldn’t be a complete or fair comparison.

The resulting wind drift for these two bullets at their respective speeds (as estimated with Equation 5.3) are shown in Table 13.2. For comparison purposes, the .30 caliber 155 grain Lapua Scenar Palma bullet, which has a form factor very close to the G7 standard projectile, is shown for comparison.

It’s interesting to note that the 155 grain Palma bullet at 3000 fps has almost as much muzzle energy as the .284 Winchester (3095 ft-lb for the Palma vs. 3130 ft-lb for the .284). Granted, the Palma load is a considerably hot load for the .308 Winchester, whereas the .284 load represents a more moderate charge.

Notice the relationship between the profiles of the bullets and their form factors (i7). The longer nose of the 7mm VLD’s is the main feature that drives the form factor down into the 0.94 area. Another way to view the form factor is to observe that the *drag coefficient* of a bullet with a G7 form factor of 0.94 has 94% of the standard projectile’s *drag coefficient* at any speed. The form factor of the 7mm bullets is about 6% better than the form factor of the Lapua Palma bullet. However, the ballistic coefficient of the 7mm bullets is way more than 6% better. The reason why is because the sectional density of the 7mm bullets is greater than that of the Palma bullet.

The wind drift numbers in Table 13.2 indicate that the 168 grain and 180 grain 7mm bullets exhibit about the same level of wind deflection when a fair comparison (equal muzzle energy) is made. Note that just because both bullets have the same kinetic energy at the muzzle, this *does not* imply equal recoil. Recoil is tied to conservation of momentum, which is altogether different from kinetic energy. *The heavier bullet will generate more recoil when fired with the same muzzle energy than a lighter bullet.* The reason why has to do with the difference between kinetic energy and momentum, and is beyond the scope of this study. Just know that recoil is greater for the heavier bullet in this comparison.

So how significant is the difference in wind drift: 64.2" vs 62.3"? That's only 1.9" difference in a 10 mph crosswind at 1000 yards, which is 3%. Is that *really* enough to make a difference on the standard NRA Long Range target with its big scoring rings? How often are shots really that close to the line that such a small difference in ballistic performance matters? In an attempt to shed some light on this question, we turn to modeling and simulation.

Modeling and Simulation

So there is 1.9" difference in the wind drift of two bullets. How does that play out on the target over time? My approach is to simulate the firing of multiple 20 shot, 1000-yard slow fire prone matches. In order to thoroughly investigate the impact of a 1.9" difference in wind drift on the 1000 yard target, I'll model three different scenarios intended to represent various levels of shooter skill. The first comparison will be made assuming a *novice* shooter with a below average hold, and below average ability to read wind conditions. The second scenario will be for an *average shooter* with an average hold and an average ability to call wind. The final comparison will represent an *elite shooter* with a stellar hold, and the ability to call wind nearly perfectly.

A. Performance Comparison for the Novice Shooter

So how do we model the *novice* shooter? The specific criteria for describing the abilities of a novice shooter are arguable. I have in mind the typical beginner shooter, possibly classified Marksman or Sharpshooter. I chose the following set of abilities: The Novice shooter's equipment and hold are barely good enough for a ten ring (20") sized group at 1000 yards in no wind conditions. He can judge the effect of a crosswind within +/- 5 mph 95% of the time[21]. I'm assuming there is sufficient wind to make a +/- 5 mph error possible. What kind of scores will the novice shooter produce given his abilities, and the 7mm bullets in Table 13.2? Figure 13.3 shows three *virtual* targets that characterize the likely performance of the novice with the three bullets.

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[21] This means that the standard deviation of wind estimation error is 2.5 mph. (+/- 2 standard deviations give you a 95% confidence interval.) A normal distribution is assumed for the wind estimation error. This simply insures that extreme error is less likely than mild error.

Novice Shooter

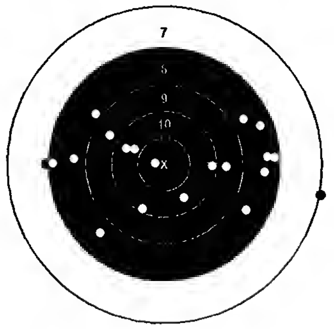
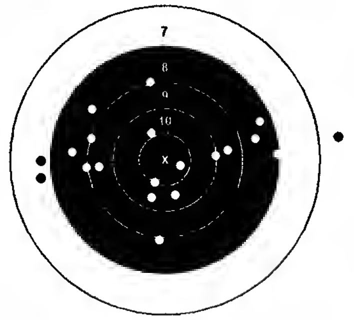
168 grain VLD	180 grain VLD
	
Average Score: 170-1X	Average Score: 171-2X

Figure 13.3. The graphics shown represent a typical target shot by a novice for the different bullets. Average score is a result of simulating the *virtual match*50 times. For reference, the 10 ring is 20" in diameter.

Figure 13.3 shows that for the novice, there is effectively no difference between the two 7mm bullets. In fact, over the course of 50 simulated matches, the 168 grain VLD's produce a lower average score of only 1 point and 1 X. The scores of the 50 virtual matches ranged from about 155 to 185, with the averages being close to 170 in both cases. This goes to show that for the novice shooter, the small benefit of the higher BC bullet is barely noticeable, there's just too much *scatter* for the small difference to affect anything.

B. Performance Comparison for the Average Shooter

I'll characterize the *average* shooter as an expert to master level shooter who has the ability and equipment to shoot a 20" group in no wind conditions. The average shooter is able to call wind within +/- 3 mph of its true value 95% of the time. Figure 13.4 shows the simulated results of virtual targets fired by an average shooter, using the same bullets as the novice shooter above.

Once again, just like for the novice shooter, *the average shooter does not benefit from shooting the 180 grain VLD's compared to the 168 grain VLD's.* For the average shooter, there is still too much *scatter* for the small benefit of the higher BC to make a practical difference. We are focusing on two specific 7mm bullets here, but this basic analysis can be applied to any two bullets that are very close in wind deflection. The bottom line is that the small difference just doesn't show up in the score. Also remember that this analysis is specific to the target. In other words, *a target with smaller scoring rings like the F-class or Benchrest targets will reflect a slight ballistic advantage more clearly than a target with larger scoring rings.*

Average Shooter

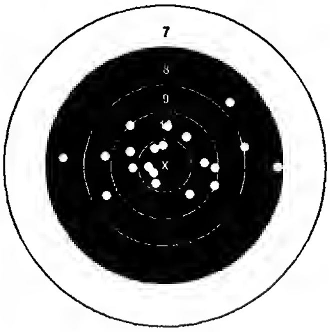
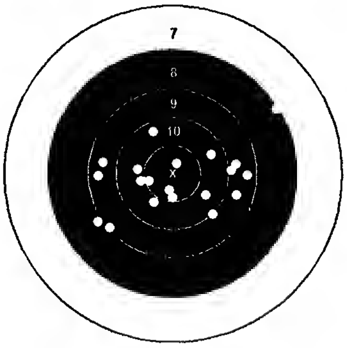
168 grain VLD	180 grain VLD
	
Average Score: 189-5X	Average Score: 189-4X

Figure 13.4. The graphics shown represent a typical target shot by an average shooter for the different bullets. Average score is a result of simulating the virtual match 20 times.

So far we've shown that both novice and average shooters can't really tell the difference in the wind drift of the two bullets. What about the elite shooter?

C. Performance Comparison for the *Elite* Shooter

I'll describe the elite shooter as someone capable of shooting a 10" group in no wind conditions. In other words, if the group is perfectly centered, the elite shooter will just be able to break the existing long range (any-sight) record of 200-19X in no wind conditions.

Elite Shooter

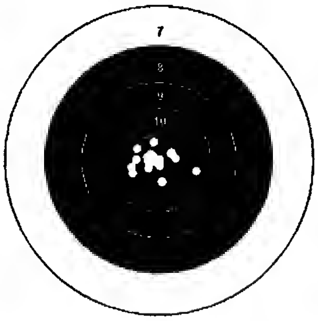
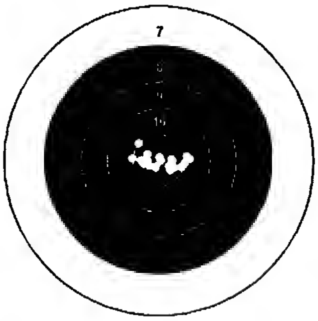
168 grain VLD	180 grain VLD
	
Average Score: 200-15X	Average Score: 200-16X

Figure 13.5. The graphics shown represent a typical target shot by an elite shooter for the different bullets. Average score is a result of simulating the virtual match 20 times.

The *elite* shooter is able to judge the crosswind speed within +/- 1 mph for 95% of his shots.

As you can see, even for the elite shooter, the minor ballistic advantage of the slower, higher BC bullet is minimal even after averaging 20 virtual matches. Running the set multiple times, I was able to produce averages that slightly favored the 168 grain VLD, but in the long run, the 180 VLD has a very slight advantage, even if it can only be detected by elite shooters.

Modeling and simulation can be risky business, both for the person *doing* the modeling, and for the person looking at the results. For both sets of people, it's important to understand the limitations and scope of the analysis.

The modeling and simulation I'm presenting here is only focused on the external ballistic performance of the bullets in the specific application of long range, NRA long range prong shooting. My simulation doesn't capture the effects of: loose slings or sights, slam fires, rain, sweat and/or sand in your eyes and lenses, heat exhaustion, fire ants, stuck casings, or cease fires for boats in the impact area. All of these and many more are real problems for long range prone shooters that affect scores. The intent of my modeling is to focus in on one aspect; *wind drift*, and isolate its effects on scores for different bullets. This is something that's hard to do in the real world which is why it can be hard to tell how many dropped points were for wind, and how many were caused by other things. The business of looking at virtual matches is an academic exercise intended to put the basic wind drift numbers into the context of a specific shooting scenario for a specific target.

Conclusions

Wind drift is the most important measure of exterior ballistic performance for long range target shooting at known distance. *In order to perform a fair ballistic comparison of wind drift between the two bullets, the muzzle velocity of the heavier bullet has to be less than the lighter bullet.* The velocity was scaled by setting the kinetic energy equal at the muzzle, which is the same as assuming equal average chamber pressure. Only in this way can a completely fair comparison be made between bullets of different weight. The heavier, higher BC bullet going slower has a slight ballistic advantage over its lighter counterpart in terms of wind drift. However, the advantage is immaterial for novice and average shooters. Based on the results of 20 virtual matches, it's even questionable if elite shooters are able to capitalize on the tiny ballistic advantage of the heavier bullet.

The analysis focused on prone shooting with the NRA long range target. It's quite possible that the same analysis done for F-class shooting on F-class targets with their smaller scoring rings would have resulted in different conclusions. Smaller scoring rings are less forgiving, and could possibly resolve a performance difference measured in points, between these two bullets.

As far as ballistic performance and its relationship to scores fired on the NRA Long Range Prone target for the two bullets considered, we can say the following:

> *If the difference in ballistic performance is small, like ~2" of wind drift in a 10 mph crosswind at 1000 yards, then it is unlikely to significantly affect scores fired on the NRA Long Range Prone target for shooters of any skill level.*

The next chapter will expand the example analysis presented in this chapter to other shooting disciplines, and attempt to draw some more general conclusions about what performance differences can be considered *significant* for other shooting applications.

Chapter 14: Generalized Score Shooting Analysis

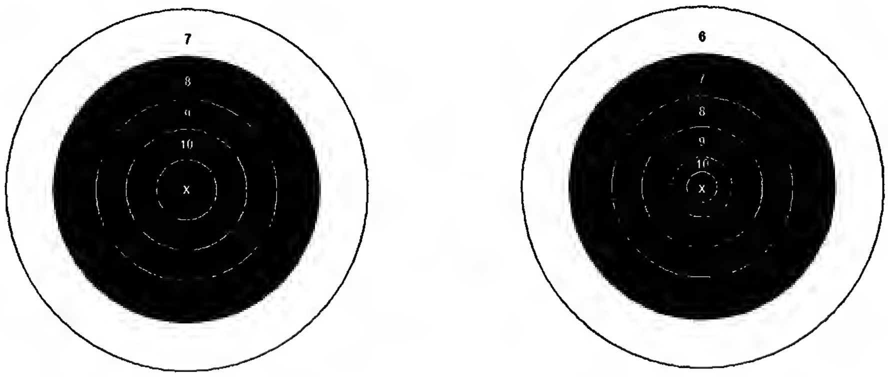
The previous chapter focused on two slightly different bullets in a specific application. The only real difference between the two bullets was weight, which affects BC and muzzle velocity. The resulting difference in ballistic performance was quantified in terms of points on an NRA long range bulls eye target. The basic conclusion is that there's not enough difference in the ballistic performance of the two bullets to account for even one point in average score, regardless of the skill level of the shooter.

That analysis was valuable for that particular case, but what if you shoot F-class which uses a different target? Does the 1.9" of wind drift at 1000 yards make a difference on a target with smaller scoring rings? This chapter will first investigate that specific question, then present some more general analysis trends and guidelines that you can use to help make decisions about your equipment and prioritize your training efforts. After specific targets used for competition are analyzed, we'll look at how to apply the analysis to irregularly shaped targets for hunting and tactical applications.

The F-class Target

The standard NRA long range prone target and the long range F-class target are shown side by side in Figure 13.1. Since the scoring rings on the F-class target are smaller than the prone target, it's very possible that a 1.9" difference in wind deflection could have a real effect on score. To investigate the effect, I'll take the same modeling and simulation approach as used in the last chapter, but with slightly modified characteristics for the *novice, average*, and *elite* shooter. We can assume that F-class shooters possess the same wind reading ability as prone shooter.

The main thing that's different between F-class and prone shooter is the method of supporting the rifle, and the resulting group sizes for no wind groups. For F-class shooters, the following *no wind* 1000 yard group sizes are assumed: novice 15", average 10", and elite 5". These group sizes represent the diameter of a circle that the shooter can hit 95% of the time in no wind conditions. The smaller group sizes reflect the more refined handling skills expected of more experienced shooters, as well as better developed precision of the equipment used by shooters at the higher levels. I'll skip the steps of presenting the images of F-class targets with representative groups, and go straight to the results from the computer modeling of 50 20-shot match scores. Table 14.1shows the average scores attained by the modeled prone and F-class shooters with the two 7mm bullets for each class of shooter.



Long Range Prone Target		Long Range F-class Target	
Ring	Size	Ring	Size
X	10"	X	5"
10	20"	10	10"
9	30"	9	20"
8	44"	8	30"
7	60"	7	44"
6	72"	6	60"
		5	72"

Figure 14.1. Comparison of the Long Range Prone and F-class scoring ring sizes.

The resulting scores for the prone shooter with the prone target from the last chapter are restated in Table 14.1 for comparison. You can see that unlike the prone shooter with the *big ringed* target, the F-class shooter is actually able to score at least 1 point higher on average with the higher BC 180 grain VLD compared to the slightly lower performing 168 grain VLD, even though there's such a minor difference between them (62.3" drift vs 64.2" drift in a 10 mph crosswind)

	Novice	Average	Elite
Wind reading error	+/- 5 mph	+/- 3 mph	+/- 1 mph
No wind group – Prone shooter	30”	20”	10”
No wind group – F-class shooter	15”	10”	5”
Average scores for shooters using above criteria and two different bullets having 1.9” difference in 10 mph wind deflection at 1000 yards.			
Prone score (180 VLD/168 VLD)	171-2X/ 170-1X	189-4X/ 189-5X	200-16X/ 200-15X
F-class score (180 VLD/168 VLD)	156-1X/ 155-3X	180-1X/ 176-2X	198-12X/ 197-10X

Table 14.1. Expected scores on two different targets. The F-class shooter can expect to average 1 point higher using the higher BC bullets, whereas the prone shooter probably wouldn’t notice a difference with the larger scoring rings.

Keep in mind that the analysis so far is primarily focusing on the effects of wind. A similar analysis will be done later to show the result of improving the vertical dispersion of shots.

So far we can conclude that for the two specific bullets under investigation, the slight difference in wind deflection would probably go unnoticed by a prone shooter, but will probably affect the average score of most F-class shooters by at least 1 point per match in the long run. I’d say that’s an important result, but it begs the question: how much difference in wind deflection would it take to make a real difference in the score of a *prone* shooter on the bigger target? This leads into the generalization part of the chapter, and some important rules of thumb that you can use to make informed decisions about your long range shooting equipment.

Generalizing the Analysis

In an effort to demonstrate the effect of wind uncertainty and deflection on score, I compiled the tables of simulation data that are included at the end of this chapter. I’ll include a short snippet of one of the tables here for discussion purposes.

As indicated by the table header, this data is for the 1000 yard prone target, and a rifle/shooter combination that’s able to shoot 20” groups in no wind conditions. As a more complete description of the accuracy, we can say that 95% (19/20) shots will hit a 20” circle.

Prone 1000 yard Target *rifle/shooter capable of 20" groups in no wind (average)						
		+/- 1 mph	+/- 2 mph	+/- 3 mph	+/- 4 mph	+/- 5 mph
Wind deflection for a 10 mph crosswind at 1000 yards	78	198-13X	192-11X	185-4X	173-3X	161-3X
	80	197-6X	192-9X	183-6X	172-3X	161-1X
	82	198-12X	192-10X	183-4X	171-3X	159-2X
	84	197-11X	191-8X	181-6X	171-3X	157-2X
	86	198-17X	190-6X	181-6X	168-4X	158-1X
	88	198-11X	191-6X	181-7X	167-2X	157-2X
	90	197-10X	191-4X	181-5X	167-0X	153-3X
	92	197-14X	189-7X	180-3X	165-3X	151-1X
	94	197-7X	190-5X	178-3X	163-4X	148-2X
	96	197-11X	188-4X	177-6X	162-2X	146-3X
	98	197-13X	188-4X	178-3X	160-1X	145-3X
	100	197-14X	188-2X	176-4X	158-3X	147-0X
	102	196-7X	187-3X	175-7X	159-3X	141-3X
	104	197-5X	188-7X	172-7X	157-1X	143-2X
	106	196-10X	188-6X	172-5X	153-3X	139-2X
	108	196-7X	186-4X	171-2X	154-2X	140-2X
	110	196-5X	185-5X	170-1X	151-2X	137-4X

Table 14.2. Statistical model of expected scores based on inherent grouping ability, wind uncertainty, and ballistic performance.

In statistical terms, the standard deviation of the dispersion is 5". Plus or minus 2 standard deviations defines the 95% confidence interval. In this case, +/- 2*5" is +/- 10", so that 95% of the shots are expected to land in a 20" circle. A normal distribution is assumed to insure that impacts near the center of the group are more likely than impacts near the edge of the group. The scores in Figure 14.2 reflect this central tendency.

You may be reading my description of an *average* shooter as being capable of 20 inch groups and thinking *"20 inch groups would **clean** the long range prone target; that's not average!"* Remember that for this exercise, I'm assuming no wind and that the groups are perfectly centered on the target which is probably unlikely, especially for someone shooting 20 inch groups.

Truthfully, I don't think the *normal distribution* assumption or the *centered group* assumptions are 100% valid, but they're necessary for proceeding with the analysis and demonstrating the relevant trends without turning this into a math book. The same normal distribution is applied to the wind uncertainty. For example, the +/- 3 mph uncertainty in the column headers indicates 95% confidence that the wind uncertainty is +/- 3 mph or less for each shot. In other words, for 19 out of 20 shots, the shooters judgment of the crosswind speed is not off by more than 3 mph in any direction.

On the left side of Table 14.2 is the deflection of the bullet in inches, for a 10 mph crosswind at 1000 yards. This number is easily obtained with the included software using the BC and muzzle velocity of a particular round. To make an estimate of a likely score for a certain combination of variables, first you find the table that characterizes your discipline/target (prone or F-class). Next, look for the small print below the Table title that indicates the approximate group size that you and your equipment are capable of for 20 shots in perfect (no-wind) conditions. For prone shooters, the options are 10", 20" or 30" (elite, average and novice). F-class options are 5", 10" and 15". After you've found the right table, look for the appropriate column header that describes your particular wind uncertainty. Note that in difficult conditions, a very good wind reader might have +/- 3 or 4 mph of wind uncertainty. Likewise, a novice shooter might have the same wind uncertainty in relatively calm conditions. Table 14.3 can be used as a guide to estimate wind uncertainty for various wind conditions and shooter skill levels. Once the appropriate column of wind uncertainty is identified, find the row that matches your ballistics (inches of deflection for a 10 mph crosswind at 1000 yards). That piece of data can be obtained using the included software and appropriate inputs.

Let's take a stab at using the data tables to estimate the approximate score that can be expected for a couple scenarios. First consider an *elite prone* shooter capable of *10" groups in no wind conditions*. This shooter is also an *elite wind reader*, shooting a rifle with very good ballistics having only *60" of deflection for a 10 mph crosswind at 1000 yards*. According to Table 14.3, we can expect this elite shooter to have about *+/- 2 mph of wind uncertainty* in his wind calls for *medium difficulty wind conditions*. Table 14.4 at the end of the chapter is the right table for this case, and indicates a predicted score of 197-9X. This seems like a likely outcome for the given scenario.

Condition	Novice	Average	Elite
Easy	+/- 3 mph	+/- 2 mph	+/- 1 mph
Medium	+/- 4 mph	+/- 3 mph	+/- 2 mph
Difficult	+/- 5 mph	+/- 4 mph	+/- 3 mph

Table 14.3. Approximate guide to estimating crosswind uncertainty for various wind conditions and shooter skill levels.

For the next example, we'll consider an *average F-class* shooter with *novice wind reading ability*, shooting a rifle with poor ballistic performance which has *100" of wind deflection in a 10 mph crosswind at 1000 yards*. The conditions are considered *difficult*. According to Table 14.3, we can expect about *+/- 5 mph of wind uncertainty* for this case. Table 14.8 indicates that a score of 122-0X can be expected for this combination. That's a pretty low score, but certainly not unrealistic for an *average shooter* with *novice wind* *reading skills* in *difficult conditions* on the *F-class target* with a rifle having *poor ballistic performance.*

The previous two examples were presented only to illustrate how to use the tables, but the point of our analysis is not to figure out what scores we're capable of shooting with our current equipment and skill level. The point of this model is to use it to study the trends, and come to some more insightful conclusions about how to improve scores.

The first and most obvious thing to point out is the fact that in all of the tables for all shooter skill levels and both prone and F-class competition, *the best thing you can do to improve your score is to learn to become a better wind reader!* Reducing the uncertainty of your wind calls goes farther towards improving your scores than any single other thing, regardless of your skill level or discipline.

Consider the average F-class shooter in the example above (novice wind reading abilities, 100" of deflection per 10 mph) who the model predicts an average score of 122-0X for in difficult conditions. If this shooter can reduce the uncertainty in his wind judgment by just 1 mph (improving from *novice* to *average* wind reading ability), he can expect his scores to improve from 122 to 138 in difficult conditions, 138 to 160 in medium conditions, and 160 to 176 in easy conditions. That's an average of 18 points improvement in average score in all conditions, just by removing 1 mph of uncertainty from the wind calls.

Now let's see how the shooter does if he focuses on improving the ballistic performance of his equipment in an effort to improve his score. If the shooter in this example is able to squeeze another 150 fps out of his loads, he may reduce his deflection from 100" to 94" in a 10 mph crosswind, a reduction of 6". According to the tables, this kind of improvement can be expected to increase his score from 122 (assuming no improvement to the novice wind reading skills) to 130 in difficult conditions, 138 to 142 in medium conditions, and 160 to 164 in easy conditions for an average improvement of just over 5 points in score for the +150 fps improvement in muzzle velocity and the 6" less wind deflection that comes with it.

In review, the F-class shooter in this example can improve his score by an average of 18 points in all conditions by removing +/- 1 mph of wind uncertainty from his wind calls, and he can improve his average score by 5 points by increasing the muzzle velocity of his bullets by 150 fps. The clear conclusion we can reach from studying these trends is that *you can increase your score much more thru improving your wind reading abilities than by stressing your components to achieve higher velocities.*

Next consider the *elite prone shooter* who has *average wind reading abilities* shooting a rifle with very good ballistic performance which only has *60" of deflection in a 10 mph crosswind at 1000 yards.* According to the model, this shooter with average wind reading ability can expect to have about +/- *3 mph of uncertainty in his wind* calls in *average* conditions, and can expect average scores around 192-7X. If this shooter improves his wind reading skills from *average* to *elite*, his wind uncertainty goes from +/- 3 mph to +/- 2 mph in *medium difficulty* conditions, and his score will improve to about 197-9X, or about 5 points. If this shooter improves the ballistic performance of his equipment and it results in 5" less wind deflection, his scores would improve from about 192 to 193 with average wind reading skills. It's very hard to reduce wind deflection by 5", and it only results in one additional point in average score on the prone target. Reducing the uncertainty of wind estimation stands to increase the average score by 5 points for the same shooter. As with the F-class example, the conclusion is clear: *there is a lot more benefit to be had by learning to read wind better than by making modest improvements in ballistic performance.*

This model is presented as a tool for doing trend analysis. My estimates of wind uncertainty for various shooters in different conditions are best guesses, and I don't claim that they're always accurate in every case. The calculated average scores are the average of 50 simulated matches, and their quite a bit of variation around the averages which is why there is some inconsistent data in the tables (scores and X counts don't strictly increase or decrease). The model was created using a non-deterministic, statistical approach which is why it contains some imperfections. Furthermore, the model is only looking at the effects of wind uncertainty, and not the many other factors that come into play in a typical 20-shot string of fire.

The shooter model in this chapter was developed for the purpose of illustrating the approximate relationship between ballistic performance/wind uncertainty and nominal scores to be expected on two types of targets. This relationship is most valuable when used to analyze trends, as the previous examples illustrate.

All of the examples showed overwhelmingly that the best way to improve scores is to improve wind reading as opposed to making modest improvements in ballistic performance. However, *you shouldn't conclude that improving ballistic performance is not worthwhile.* Of course the best way to maximize your score is to put effort into *all things* that stand to maximize score. Ballistic performance is something that is established as you make decisions in the pre-season about your equipment including caliber, bullets, bullet modifications and muzzle velocity. The ballistic performance of your equipment is what it is when you arrive at the range, and there's nothing you can do to affect it while you're shooting. Your wind reading ability is something that you can learn to improve on each shot of the match as you carefully observe the indicators, and concentrate on correlating cause and effect.

Optimizing your equipment's ballistic performance and developing wind reading skills are two independent tasks, each having a benefit of their own. There's no reason to ignore either aspect (ballistic performance or wind reading skills), and your priorities and efforts should be guided by the facts.

Reducing Vertical Dispersion

The previous analysis has focused on wind, and losing points from shots that are dispersed horizontally across the target face. For certain, wind is the biggest problem and responsible for more lost points than anything else. We looked at ways to reduce the horizontal dispersion by improving ballistic performance and wind reading accuracy. It's also possible to prevent losing points to wind by improving the vertical size of your group. That statement may seem strange at first, but if you consider the nature of a target with round scoring rings, it's quite apparent. Consider the Long Range Prone target in Figure 14.2.

Consider a shot on the 1000 yard target that has 10" of horizontal error. The horizontal error is a common result of wind effects not being perfectly judged, and happens to some extent on every shot. If the shooter is able to maintain good vertical consistency, the shot with 10" of wind deflection hits the line of the 10-ring, is scored a 10, and no points are lost. However, if the shooter cannot maintain a narrow line of elevation with his rifle/shooting ability and the shot happens to hit high or low from center, then the same 10" of wind error will strike in the 9 ring, and result in the loss of a point. Before I get into some ways to reduce vertical dispersion, let's look at a couple examples of how to estimate the results of an improvement.

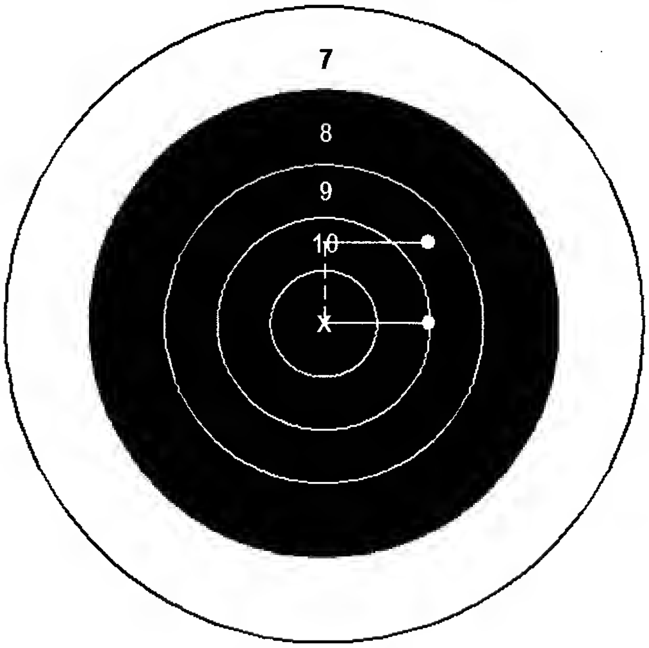


Figure 14.2. The combined effects of a vertical and horizontal error can lead to the loss of a point, whereas either one on their own would not.

The tables at the end of this chapter that we've been using to gain insight into improving the wind problem can be used to study the effects of general dispersion as well. There are 3 tables each for Prone and F-class targets. Each table represents a different level of *inherent precision* that the shooter/rifle combination is capable of.

For the prone shooter, the three tables characterize the performance for a rifle/shooter system capable of; 30" groups (novice), 20" groups (average), and 10" groups (elite). The group size represents a circle that 95%, or 19/20 of the shots will land in under perfect, no wind conditions.

Let's consider a *novice prone shooter* who can almost keep all the shots in a 30" group under perfect conditions. He's got *novice* wind reading skills, and is shooting in *difficult* conditions. We'll at least give him a rifle that has good ballistic performance and a respectably low*58" of wind drift in a 10 mph crosswind at 1000 yards*. In *difficult* conditions, the +/-5 mph crosswind uncertainty will cause this shooter to drop (on average) about 26 points, and score around 174. If this shooter works to reduce the size of his groups from 30" down to 20" while keeping his ballistic performance and wind reading abilities the same, the 30" to 20" improvement in group size will improve his average scores by about 4 points from 174 to 178 in difficult conditions. If the shooter works hard to further refine his equipment and position until he's an elite shooter, capable of 19/20 shots in a 10" group under perfect conditions, he can expect his score to improve by a couple more X's. The shooter will have to now elevate his wind reading abilities above the novice level in order to make substantial improvements to his score. Refining one's equipment and hold to achieve less vertical dispersion has a clear effect on one's score, regardless of the wind conditions and the shooters ability to judge them.

It's easy to get wrapped around the axle on all the technical details involved in maximizing score, and prioritizing efforts to that end. Remember to always keep the nature of the contest in focus. Competitive score shooting is a contest of *accuracy* and *precision*. Precision is achieved with quality equipment and well-made ammo. Accuracy is achieved with properly adjusted sights and accurate corrections for the wind.

The final topic in this section on general analysis will examine the consequences of not properly centering a group.

Centering the group

The phrase: "easier said than done" applies more to group centering than any other fundamental of score shooting. It's painfully obvious that you should do your best to center your group, but it's very difficult to do. Next to wind effects, poorly centered groups are probably the biggest reason for losing points in a score match. The basic challenge is that you can only see your last shot. It's a good idea to record (plot) your shots so you can see patterns forming and be able to adjust the sights to center the group. The reality is that writing while shooting is a distraction that takes your focus off the wind. The question everyone needs to answer for themselves is: *is it a worthwhile distraction?* In other words, will you help your score more by distracting yourself with a plot to center the group, or by focusing solely on the wind? Personally I've gone back and forth with different plotting schemes in an effort to keep the group centered and have a historical record of the wind strength. In the end, I feel like I lose more points because of wind conditions I miss while reading/writing in my plot book than the points I save by having the plot. In team shooting where people are available to plot, a plot can be kept and used to good effect without distracting the shooter or coach.

I'm not going into the same depth about the effects of non centered groups as I did with wind effects and group size. The score shooter should simply do his best to center groups as well as possible. The only real decision to make is whether to plot the shots while shooting or not. Here's one example to somewhat quantify the effects of non-centered groups on score. Consider the average prone shooter capable of putting 19/20 shots in a 20" group at 1000 yards with no wind. If the group is perfectly centered, the shooter can expect a score of 199 with about 14 X's. If the group is off center by just 5" in any direction, the average score falls to around 197-7X. If the group is off center by 10", the average score will fall to around 186-1X.

The point is that a little bit of imperfection in zero (5") has a minor affect on score, but a little more imperfection (10") can have a big effect. One of the challenges of centering the group is that you don't know where the center is forming until a good number of shots have been fired. Even then, each shot changes the collective average.

Having a well established zero for your rifle goes a long way toward being able to center a group. For example, if you take the sights off the rifle every time you shoot it and they go back on just a little different each time, you're essentially re-zeroing the rifle every time you shoot it. If you leave the sights on, there are no loose screws in the rifle, your position is repeatable and consistent, you always find your natural point of aim, then your zero will be much less likely to wander, and this will promote more centered groups.

		Prone 1000 yard Target-elite shooter *rifle/shooter capable of 10" groups in no wind				
		+/-1 mph	+/-2 mph	+/-3 mph	+/-4 mph	+/-5 mph
Wind deflection for a 10 mph crosswind at 1000 yards	50	200-17X	198-12X	195-12X	190-5X	185-4X
	52	200-17X	198-11X	194-5X	188-7X	183-6X
	54	200-17X	198-16X	193-6X	188-7X	181-5X
	56	200-17X	198-16X	193-6X	187-5X	180-4X
	58	200-16X	197-13X	191-8X	186-3X	178-5X
	60	200-16X	197-9X	192-7X	185-10X	175-3X
	62	200-16X	197-8X	191-9X	185-6X	174-3X
	64	200-15X	197-11X	189-5X	183-5X	174-2X
	66	200-15X	196-12X	190-8X	183-6X	174-6X
	68	200-15X	196-5X	189-8X	182-2X	172-3X
	70	200-15X	196-7X	188-6X	180-7X	171-5X
	72	200-15X	196-10X	188-4X	180-3X	168-6X
	74	200-14X	195-10X	187-4X	180-6X	166-4X
	76	200-14X	194-6X	186-5X	176-5X	163-5X
	78	200-14X	194-11X	185-2X	177-2X	165-5X
	80	199-14X	194-12X	185-4X	174-2X	161-1X
	82	200-14X	193-10X	183-9X	174-4X	160-7X
	84	199-13X	193-9X	185-8X	171-2X	162-3X
	86	199-13X	192-5X	183-6X	170-5X	156-6X
	88	199-14X	193-8X	182-4X	169-2X	158-4X
	90	199-13X	192-9X	180-4X	168-7X	152-3X
	92	199-12X	190-7X	180-3X	168-6X	150-5X
	94	199-13X	190-10X	180-5X	162-4X	148-5X
	96	199-12X	191-5X	180-4X	162-5X	145-3X
	98	199-12X	189-6X	178-6X	162-3X	145-3X
	100	199-12X	191-6X	178-2X	163-2X	144-2X
	102	199-12X	190-11X	175-4X	161-4X	147-3X
	104	199-11X	188-8X	177-5X	159-2X	144-7X
	106	199-12X	188-8X	174-4X	157-2X	137-4X
	108	198-12X	188-9X	172-4X	154-1X	137-1X
	110	198-11X	187-3X	173-3X	155-2X	137-5X

Table 14.4. Scoring model for elite prone shooter.

Prone 1000 yard Target-average shooter *rifle/shooter capable of 20" groups in no wind					
Wind deflection for a 10 mph crosswind at 1000 yards	+/-1 mph	+/-2 mph	+/-3 mph	+/-4 mph	+/-5 mph
50	198-10X	197-8X	193-7X	188-1X	182-1X
52	198-7X	196-13X	192-6X	185-2X	181-8X
54	199-12X	196-13X	191-7X	186-3X	181-1X
56	199-12X	196-4X	191-6X	184-7X	181-3X
58	199-11X	196-6X	190-9X	184-6X	178-3X
60	198-10X	196-11X	190-3X	183-6X	176-1X
62	198-14X	194-8X	189-4X	183-1X	174-3X
64	199-11X	194-9X	189-5X	182-3X	172-4X
66	198-8X	194-11X	188-4X	180-4X	172-4X
68	198-10X	194-7X	187-6X	179-4X	171-2X
70	198-15X	194-13X	187-4X	180-8X	168-3X
72	198-12X	192-8X	186-8X	177-7X	164-5X
74	198-9X	193-6X	186-2X	177-4X	165-5X
76	198-12X	193-4X	184-5X	175-6X	163-4X
78	198-13X	192-11X	185-4X	173-3X	161-3X
80	197-6X	192-9X	183-6X	172-3X	161-1X
82	198-12X	192-10X	183-4X	171-3X	159-2X
84	197-11X	191-8X	181-6X	171-3X	157-2X
86	198-17X	190-6X	181-6X	168-4X	158-1X
88	198-11X	191-6X	181-7X	167-2X	157-2X
90	197-10X	191-4X	181-5X	167-0X	153-3X
92	197-14X	189-7X	180-3X	165-3X	151-1X
94	197-7X	190-5X	178-3X	163-4X	148-2X
96	197-11X	188-4X	177-6X	162-2X	146-3X
98	197-13X	188-4X	178-3X	160-1X	145-3X
100	197-14X	188-2X	176-4X	158-3X	147-0X
102	196-7X	187-3X	175-7X	159-3X	141-3X
104	197-5X	188-7X	172-7X	157-1X	143-2X
106	196-10X	188-6X	172-5X	153-3X	139-2X
108	196-7X	186-4X	171-2X	154-2X	140-2X
110	196-5X	185-5X	170-1X	151-2X	137-4X

Table 14.5. Scoring model for average prone shooter.

Prone 1000 yard Target-novice shooter
*rifle/shooter capable of 30" groups in no wind

Wind deflection for a 10 mph crosswind at 1000 yards

	+/-1 mph	+/-2 mph	+/-3 mph	+/-4 mph	+/-5 mph
50	195-10X	193-8X	190-2X	184-6X	180-4X
52	195-8X	193-5X	188-5X	183-3X	178-3X
54	195-11X	193-7X	188-6X	183-4X	176-4X
56	194-9X	192-7X	187-5X	182-4X	175-6X
58	194-7X	192-4X	187-3X	183-3X	174-3X
60	194-11X	192-10X	187-5X	180-3X	174-3X
62	195-9X	191-8X	185-6X	179-6X	171-2X
64	194-11X	191-5X	185-5X	179-2X	170-1X
66	194-9X	191-4X	184-4X	179-6X	170-0X
68	194-9X	190-6X	183-4X	176-2X	166-2X
70	194-5X	189-3X	183-3X	175-2X	166-2X
72	195-10X	190-7X	181-3X	174-1X	165-2X
74	194-9X	188-4X	181-3X	171-2X	164-5X
76	194-7X	189-7X	181-4X	171-3X	162-4X
78	194-2X	189-5X	182-3X	170-1X	160-1X
80	194-6X	187-4X	180-5X	172-2X	155-3X
82	193-6X	187-3X	180-4X	168-3X	154-4X
84	194-7X	187-6X	179-0X	165-1X	155-1X
86	194-7X	188-2X	178-4X	167-0X	154-4X
88	193-10X	186-5X	177-3X	165-3X	151-2X
90	194-7X	187-5X	176-3X	163-0X	151-0X
92	193-6X	186-4X	175-5X	162-1X	150-3X
94	193-6X	186-4X	177-3X	160-5X	148-2X
96	193-8X	185-5X	174-3X	159-1X	146-2X
98	193-9X	184-3X	171-5X	160-2X	144-4X
100	194-10X	185-9X	173-4X	154-4X	136-0X
102	193-10X	185-7X	171-1X	152-2X	141-1X
104	192-6X	184-3X	172-5X	155-1X	140-0X
106	192-5X	183-6X	171-1X	155-2X	140-1X
108	193-7X	182-4X	169-1X	153-2X	137-1X
110	193-5X	182-1X	168-6X	148-2X	132-0X

Table 14.6 Scoring model for novice prone shooter.

F-Class 1000 yard Target-elite shooter
*rifle/shooter capable of 5" groups in no wind

Wind deflection for a 10 mph crosswind at 1000 yards	+/-1 mph	+/-2 mph	+/-3 mph	+/-4 mph	+/-5 mph
50	199-10X	191-7X	185-4X	177-2X	169-3X
52	198-12X	192-9X	184-2X	175-2X	169-4X
54	198-11X	191-8X	183-3X	174-2X	165-2X
56	198-11X	189-4X	183-3X	173-1X	165-1X
58	198-10X	190-6X	181-2X	173-4X	163-4X
60	198-12X	189-10X	181-3X	171-6X	158-2X
62	198-12X	188-6X	179-2X	170-3X	157-2X
64	197-12X	189-0X	178-3X	170-3X	157-3X
66	197-6X	188-4X	177-3X	165-1X	156-3X
68	197-12X	187-4X	177-4X	162-2X	153-1X
70	196-11X	188-8X	176-4X	165-5X	150-0X
72	196-11X	185-4X	174-5X	163-5X	146-2X
74	196-5X	185-5X	175-2X	162-1X	143-1X
76	196-7X	185-6X	173-2X	161-2X	146-4X
78	195-11X	183-4X	173-4X	156-3X	140-1X
80	196-12X	184-7X	171-2X	157-3X	142-0X
82	194-8X	183-3X	170-4X	154-1X	137-2X
84	195-11X	183-5X	170-5X	153-1X	133-3X
86	194-6X	182-5X	166-2X	148-3X	138-1X
88	194-4X	182-7X	164-0X	149-1X	128-0X
90	194-7X	181-3X	164-9X	150-0X	129-4X
92	194-6X	180-4X	165-2X	148-2X	132-0X
94	193-8X	180-5X	162-0X	144-2X	129-1X
96	193-6X	178-5X	161-4X	143-1X	127-0X
98	193-1X	178-3X	162-0X	141-1X	125-0X
100	192-8X	179-3X	160-5X	139-0X	128-5X
102	191-3X	176-5X	161-3X	139-2X	123-1X
104	191-8X	176-1X	157-0X	141-1X	120-2X
106	191-7X	176-3X	158-0X	133-1X	120-3X
108	191-8X	177-4X	156-2X	139-0X	119-2X
110	191-7X	174-3X	154-0X	133-3X	115-3X

Table 14.7 Scoring model for elite Fclass shooter.

F-Class 1000 yard Target-average shooter
*rifle/shooter capable of 10" groups in no wind

Wind deflection for a 10 mph crosswind at 1000 yards	+/-1 mph	+/-2 mph	+/-3 mph	+/-4 mph	+/-5 mph
50	197-8X	190-3X	184-2X	176-2X	168-0X
52	197-7X	190-7X	183-3X	175-5X	167-2X
54	196-9X	189-6X	181-1X	174-3X	166-1X
56	196-10X	189-2X	181-2X	174-1X	161-3X
58	196-9X	189-6X	180-1X	172-4X	162-0X
60	196-6X	188-4X	179-2X	170-2X	161-5X
62	195-9X	187-5X	180-1X	167-3X	160-3X
64	195-7X	188-4X	176-2X	167-3X	155-1X
66	195-10X	185-2X	177-4X	164-2X	154-1X
68	195-3X	185-2X	175-5X	164-3X	149-2X
70	194-4X	186-5X	174-1X	162-3X	147-0X
72	194-10X	185-5X	175-1X	164-3X	146-0X
74	194-5X	183-0X	173-6X	160-5X	148-2X
76	194-11X	183-3X	172-2X	157-4X	144-2X
78	193-9X	183-4X	171-2X	156-2X	143-1X
80	194-9X	182-6X	170-1X	157-2X	141-4X
82	193-2X	181-3X	170-2X	155-1X	139-1X
84	193-6X	182-2X	167-2X	150-1X	135-1X
86	193-5X	181-2X	167-4X	150-2X	130-1X
88	193-4X	180-2X	164-3X	149-2X	131-1X
90	192-5X	180-3X	165-2X	149-2X	132-2X
92	191-4X	178-2X	163-3X	147-1X	127-2X
94	192-5X	178-3X	164-1X	142-1X	130-1X
96	191-4X	176-1X	162-2X	141-2X	124-0X
98	192-4X	177-5X	160-1X	136-0X	123-0X
100	191-8X	176-2X	160-3X	138-0X	122-0X
102	190-7X	177-2X	159-3X	139-0X	118-1X
104	190-4X	175-2X	156-3X	135-2X	113-0X
106	190-4X	176-4X	154-2X	136-2X	120-1X
108	189-5X	173-1X	154-0X	133-1X	112-1X
110	189-7X	172-1X	151-2X	134-1X	113-0X

Table 14.8 Scoring model for average Fclass shooter.

F-Class 1000 yard Target-novice shooter
*rifle/shooter capable of 15" groups in no wind

Wind deflection for a 10 mph crosswind at 1000 yards	+/-1 mph	+/-2 mph	+/-3 mph	+/-4 mph	+/-5 mph
50	194-6X	189-4X	181-2X	175-3X	166-3X
52	194-8X	187-4X	180-4X	173-4X	165-1X
54	193-6X	187-2X	180-5X	173-4X	166-0X
56	193-10X	187-5X	181-7X	170-0X	160-3X
58	193-7X	186-2X	178-2X	171-2X	161-2X
60	193-7X	186-1X	177-3X	167-2X	159-3X
62	193-5X	185-5X	177-3X	167-4X	156-1X
64	193-8X	184-4X	176-2X	166-1X	155-3X
66	193-8X	184-4X	175-3X	163-2X	150-1X
68	192-4X	184-5X	176-4X	164-1X	149-1X
70	192-9X	182-8X	173-2X	164-2X	150-2X
72	192-5X	182-4X	174-4X	160-4X	146-0X
74	191-9X	183-1X	172-0X	159-2X	141-1X
76	191-6X	182-4X	171-0X	157-1X	145-1X
78	191-6X	181-4X	172-0X	156-2X	138-0X
80	190-4X	181-4X	169-3X	152-4X	140-2X
82	190-4X	179-4X	167-4X	154-0X	139-0X
84	190-4X	180-2X	168-2X	150-0X	134-0X
86	190-4X	179-1X	166-0X	148-0X	130-2X
88	190-5X	178-2X	164-2X	150-0X	130-0X
90	190-7X	178-3X	164-3X	147-1X	126-2X
92	189-2X	177-2X	161-4X	145-1X	127-1X
94	189-5X	177-5X	163-2X	143-2X	128-2X
96	190-5X	175-2X	161-3X	139-2X	121-0X
98	189-4X	175-2X	160-3X	139-2X	123-1X
100	189-5X	175-6X	155-1X	141-0X	123-2X
102	188-4X	173-3X	158-2X	139-1X	122-0X
104	187-2X	172-2X	158-0X	135-1X	118-2X
106	188-7X	171-1X	152-0X	129-0X	117-2X
108	187-4X	173-4X	156-1X	136-0X	113-1X
110	187-2X	172-3X	150-0X	130-1X	116-1X

Table 14.9 Scoring model for novice Fclass shooter.

Chapter 15: Lethality of Long Range Hunting Bullets

Long range hunting is a challenging and rewarding activity which is growing in popularity by leaps and bounds. The availability of modern high quality components and laser rangefinders is enabling shooters to kill game animals reliably at unprecedented distances. *Unfortunately, the quality of modern equipment is outpacing the specialized knowledge that's needed to employ that equipment effectively.* This book will present some information that the long range hunter needs to get the most out of his equipment so he can make his shots with confidence.

When considering the maximum effective range of a hunting rifle, there are two major questions to answer:

1. What's the max range that the shooter/rifle is capable of *hitting* the intended game?
2. What's the max range that a bullet can *kill* the intended game?

The logical way to answer these questions is to first determine the maximum range the bullet can *kill* the game, then worry about what it takes to *hit* the animal within that range. This chapter will focus on the lethality question. The idea of bullet lethality is examined and some information is presented that will allow you to determine the maximum *lethal* range of your rifle and bullet. Once the *lethal range* of your rifle/bullet is understood, the following Chapter will discuss the considerations involved in *hitting* the animal with a lethal shot.

Lethality has a lot to do with terminal bullet performance, but that subject is outside the scope of this book. For those interested in a definitive study of terminal bullet performance, I recommend the book: *"Rifle Bullets for the Hunter"*. Lethality encompasses a lot of things. Some of them have to do with ballistics, some don't. It would be a mistake to think lethality is all about energy, or all about terminal bullet performance, or all about shot placement. These are all important pieces of the puzzle, but none of them contain everything you need to know about lethality. You can learn about proper shot placement by doing some basic research on the anatomy of your game and talking to experienced hunters. The aforementioned book is a good source to learn about terminal bullet performance. In this book, I offer the external ballistic piece of the lethality puzzle. Most of what I present about lethality in this chapter will be focused around external ballistic factors and influences including retained energy.

How Bullets Kill

To think about how a bullet kills an animal might seem embarrassingly trivial at first. Obviously the bullet kills by poking a hole in the animal! However, if you compare the *lethality* of a modern high velocity center fire rifle compared to a bow and arrow, the rifle is obviously more *lethal.* For certain the high velocity rifle bullet affects quicker kills, even for similarly sized penetrators (mushroomed bullet vs broad head). The bullet definitely has something going for it that makes it more lethal than the arrow. The most obvious difference between the two is velocity. Velocity plays a very important role in the lethality of a bullet, but there's much more to it. The hydrostatic shock of a bullet traveling thru tissue at supersonic speed is very damaging. If the shock is strong enough, it can affect the animal's brain, causing immediate incapacitation and/or unconsciousness. The strength of the shock is proportional to the velocity of the bullet. Impact velocity alone won't necessarily be *lethal* if the bullet is quickly stopped a short distance inside the animal. This is where *penetration* comes in. If the bullet strikes with sufficient *velocity* and has sufficient *mass* to retain the velocity as it penetrates, then the bullet can generate a significant hydrostatic shock that incapacitates the animal. The ability of the bullet to generate the incapacitating shock is what makes it more lethal than an arrow.

It's clear that *velocity* and *mass* are the two fundamental ballistic properties of the bullet that will determine its lethality (expansion aside for the moment). There are two physical measures involving velocity and mass: Kinetic Energy (KE) and momentum.

Kinetic energy was touched on in Chapter 11 in the section titled: *The Energy of Ballistics.* Kinetic energy is a measure of a bullet's *striking energy.* The formula for Kinetic Energy is:

$$KE = \frac{1}{2}mV^2$$

m is the mass of the bullet (equal to its weight in grains divided by 7000 divided by 32.2) and *V* is the bullet's velocity in fps. It's not important to focus on calculating kinetic energy for now, just examine the equation. Note there is one multiple of *mass* and two multiples of *velocity.* In other words, kinetic energy is influenced by *mass*, and even more so by *velocity.* Also note there are other factors like the 1/2, and the mass conversion factors. In words, *kinetic energy is an indicator of the peak level of hydrostatic overpressure (shock) the bullet can achieve on impact.*

With that in mind, consider the equation for momentum:

$$Momentum = mV$$

Again m is the mass of the bullet and V is velocity. Here we have the same situation with conversion factors, but the fundamental observation about the momentum equation is that *momentum is the product of mass and velocity.* Unlike KE where velocity was more important, momentum is equally affected by changes in mass and velocity. In words, *momentum is related to the bullet's ability to maintain velocity and a high level of hydrostatic shock as it penetrates thru an animal.*

The *rate* at which the bullet deposits its energy and momentum to the animal are partially determined by the expansion and fragmenting characteristics of the bullet. A bullet that remains un-deformed will generate lower levels of static overpressure (shock) but be able to maintain it longer. On the contrary, a bullet with equal KE and momentum that expands rapidly will generate a higher peak overpressure, but will not be able to maintain it as long.

All hunting bullets lie somewhere on the spectrum between rapid expansion and low expansion. What the low expansion bullets give up in shock they gain in penetration, and vice versa. *The basic idea is that the bullet possesses a certain amount of energy. Its momentum and its expansion properties will determine how that energy is deposited to the animal in the form of lethal shock.* The remainder of this chapter will focus on the lethality of bullets from the point of view of energy and momentum. These factors are the basic driving force behind how lethal a bullet of any construction can be.

Disclaimer:

> *It should be noted that most scientific theories/models regarding bullet lethality including the one I'm presenting are officially contested by someone, somewhere. Because of the many variables involved in lethality and the role of shot placement and the animal's internal composition and health, etc., it's very hard to establish uncontested universal truths about exactly how bullets kill. In other words, lethality is not an exact science like gravity drop or measuring distance. The lethality model I'm presenting is useful because it allows one to select a hunting bullet based on its lethality on a certain size of game. The model is based on sound reasoning, accounts for the energetics involved, and has proven to be a successful guide for selecting appropriate bullets for hunting. However it is only a model, and as such, it doesn't have to be 100% technically right in order to be useful. Consider the generations of people that navigated by the stars with the assumption that the earth was flat and at the center of*

the universe. Their model was technically flawed, but most of those people still got where they were going. There may someday be a complete, universal, practical, and uncontested model of bullet lethality. In the meantime, we have to make do with imperfect but 'useful' models.

Matunas' Optimal Game Weight Formula

In his book: *"Big Game Rifles and Cartridges"*, Edward Matunas' presented his famous formula; the Optimal Game Weight (OGW) Formula. The OGW formula is an attempt to identify the key components of a bullet's lethality, and relate them to an appropriate, or *Optimal* sized animal. Matunas' OGW Formula is:

$$OGW = V^3 W^2 \cdot 1.5 \times 10^{-12}$$

Equation 15.1

Where:

OGW is the weight, in pounds, of the optimal weight of game that the bullet can/should be used for.
V is the velocity of the bullet in feet per second.
W is the weight of the bullet in grains.
$1.5\text{x}10^{-12}$ is a constant that takes care of the units.

A quick examination of the OGW formula reveals something very interesting. Before the disclaimer, there was a short discussion about the merits of kinetic energy and momentum. Kinetic energy is ½ times mass times velocity times velocity (two multiples of velocity and one of mass). Momentum is mass times velocity. If you multiplied kinetic energy and momentum together, you would have three multiples of velocity and two multiples of mass. Look again at the OGW formula. It contains three multiples of velocity and two multiples of mass (weight) and a constant that takes care of units. In essence, Matunas' OGW formula is kinetic energy times momentum, adjusted by a constant. In other words, *the formula accounts for the essential energetic components of bullet lethality.* Once again, the formula admittedly does not account for bullet construction (rapid expansion vs deep penetration), *but it does say a lot about how much energy the bullet has to expand or penetrate with.* This is a useful model on which to base a bullet selection and maximum range analysis.

Let's exercise Matunas formula with an example. Consider a .308 Winchester with 150 grain bullets at a muzzle velocity of 2800 fps. What is the optimal game weight according to Matunas' formula?

$$2800^3 * 150^2 * 1.5\text{x}10^{-12} = \mathbf{741\ lb}$$

This formula tells us that *at the muzzle,* the 150 grain bullet should be lethal against a 741 pound animal.

Of course, very few animals are actually shot right at the muzzle. Let's see what size game this bullet is effective against at a range of 300 yards. At 300 yards, a typical .308 caliber hunting bullet will retain about 2140 fps when fired with a muzzle velocity of 2800 fps. At this range and bullet speed, the OGW formula predicts:

$$2140^3 * 150^2 * 1.5\text{x}10^{-12} = \mathbf{331\ lb}$$

331 pounds is about the weight of a large deer. The formula seems to make sense, as many deer are taken with the .308 Winchester at ranges up to 300 yards with bullets as light as light as 150 grains.

Animal	Weight
White tailed deer:	
Buck	130-300 lb
Doe	90-165 lb
Mule Deer:	
Buck	150-300 lb
Doe	100-175 lb
Black Bear:	
Male	250-600 lb
Female	90-400 lb
Elk:	
Bull	700 lb
Cow	500 lb

Table 15.1. Approximate animal weight

The previous examples show the fundamental application of the OGW formula. This is where most books and references leave off, having presented a formula and an example of how to use it.

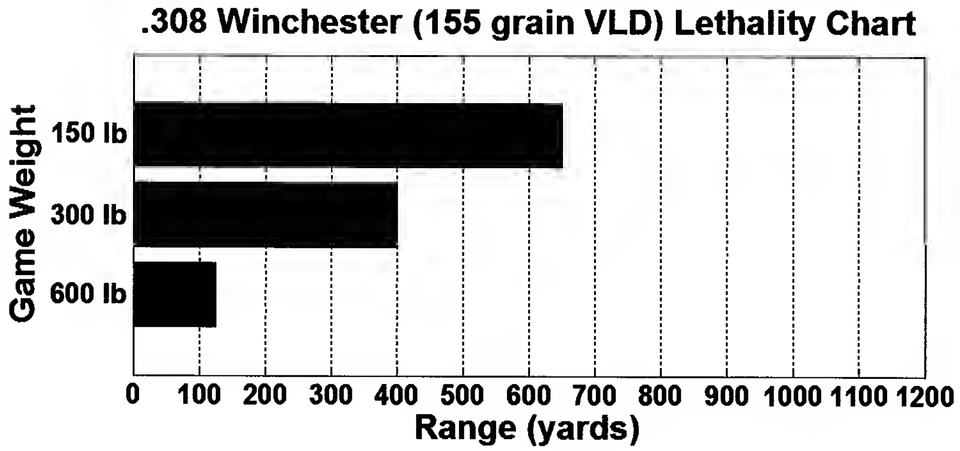
True to the promise of this book, I'll be taking this analysis a few steps farther in an effort to provide some *genuinely helpful information.* What's *really* needed is a general guide that allows hunters to select bullets based on their lethality against certain sized game at various ranges. The first step in this process is to make an educated guess at the weight of the animal being hunted. Table 15.1 can be used to approximate the weight of some common game animals.

Usually when you're selecting a bullet for hunting, you already know the approximate weight of the game you'll be hunting, and the approximate maximum range you expect to be shooting. ***Combined with a ballistics program (to give downrange velocity) the OGW formula can be used to determine the range a given bullet is lethal against a certain size game.*** The Appendix contains the details and an example of how to solve the OGW formula for velocity and use it to find effective range.

Figure 15.1 is a graphical example of how the OGW formula can be used to determine the optimal lethal range of a given bullet against 3 different weights of game. This example uses the Berger 155 grain VLD (G7 BC = 0.233) at a muzzle velocity typical of the .308 Winchester: 2850 fps.

Notice the trend in Figure 15.1 that the bullet is effective against lighter game to farther ranges than it is against heavy game. For example, the 155 VLD is optimal for a 150 pound animal out to 650 yards, but for a 600 pound animal, the optimal range is limited to 125 yards. Remember these are not *hard and fast* numbers, only guidelines to make sure that your bullets have at least the optimal amount of energy to be lethal on the intended game at the intended range.

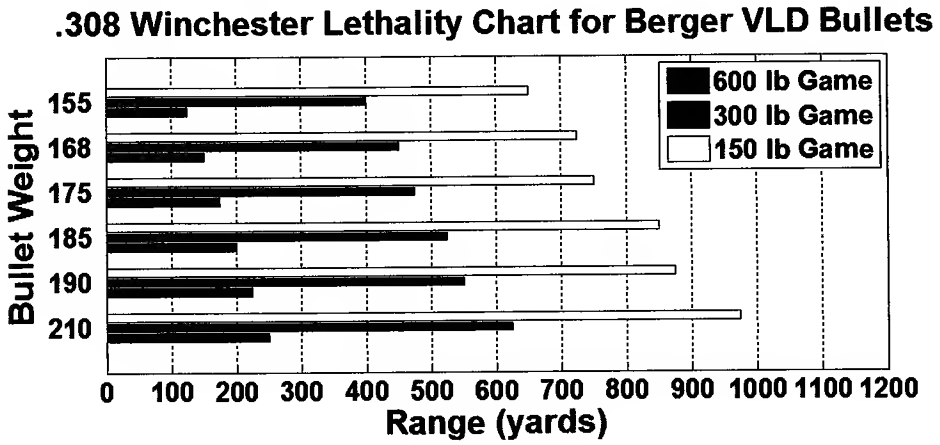
The next extension of our analysis is to study the effects of different *bullet weights* on the ranges that different sized game can be killed. We'll stick with the .308 Winchester and the Berger line of VLD hunting bullets for now (other brands will be investigated later).



Game Weight	Optimal Range
150 pounds	650 yards
300 pounds	400 yards
600 pounds	125 yards

Figure 15.1. Ranges for optimal game weight for the Berger 155 grain VLD (MV = 2850 fps) for three different sizes of game.

Figure 15.2 completes the development of the lethality charts based on the OGW formula. This chart has enough information to make an informed decision about what bullet weights (of this particular brand) are appropriate for various sized game at all ranges. For example, if you're hunting 150 lb game out to 500 yards, any bullet from 155 grains to 210 grains will be adequate for the task. If you quarry is 300 pounds, you have to select one of the heavier bullets: the 185 grain, 190 grain or 210 grain to be lethal at 500 yards. If your game is 600 pounds and you want to kill it at 500 yards, you might want to consider a bigger gun! The .308 Winchester is simply not optimized for reliable lethality on this sized game with anyof the bullets in Figure 15.2. This isn't to say the game *can't* be taken at that range, only that the bullet will have less than optimal energy to *reliably* kill animals that size according to the OGW formula.



	Bullet:	155	168	175	185	190	210
	Velocity:	2850	2738	2662	2609	2574	2449
		Optimal lethal range (yards)					
Game Weight	150 lb	650	725	750	850	875	975
	300 lb	400	450	475	525	550	625
	600 lb	125	150	175	200	225	250

Figure 15.2. Effective lethal ranges for the entire line of .30 cal Berger VLD bullets for muzzle velocities typical of the .308 Winchester.

If your game weight is somewhere between the weights listed on the lethality chart, you can simply *eyeball* the chart to estimate the range. For example, if you're loading 185 grain bullets and your game is 450 pounds (halfway between 300 and 600 pounds), you can go halfway between 200 yards (600 pound game) and 525 yards (300 pound game) which is about 360 yards.

Figure 15.2 is a good illustration of how downrange lethality is affected by bullet weight from a given cartridge. What about going to different cartridges? How do elevated muzzle velocities affect the lethality of a given set of bullets?

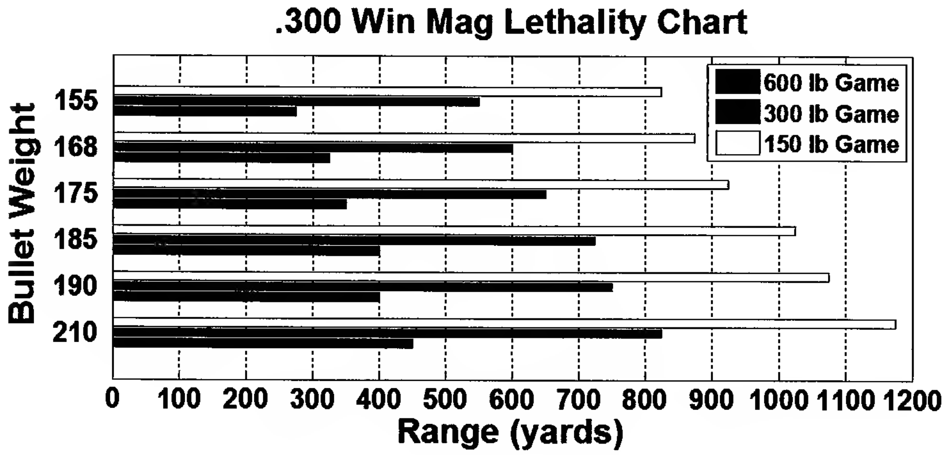
Effects of Muzzle Velocity on Lethality

For a given series of bullets, muzzle velocity is mostly determined by the cartridge. Our previous examples considered velocities typical of a .308 Winchester. Let's examine the lethality of that same set of bullets fired from a .300 Winchester Magnum.

A .300 Winchester Magnum is able to achieve several hundred fps higher muzzle velocity than the .308 Winchester, so it reasons that the bullets will be lethal on game to ranges greater than the .308. Figure 15.3 shows the lethality chart for bullets fired from the .300 Winchester Magnum.

Let's take a critical look at the lethal ranges for the .300 Winchester Magnum compared to the .308 Winchester with the same bullets. The lethality charts indicate that the max range of the .308 Winchester is achieved with the heaviest bullet (210 grain VLD) against the lightest game (150 pounds). The distance is 975 yards for this combination. The .300 Winchester Magnum also achieves its greatest range with the 210 grain VLD's against the 150 pound animal, but the range is 1175 yards. The .300 Winchester Magnum achieves 300 fps more velocity with the 210 grain bullets (2749 fps vs 2449 fps) which gives it a 200 yard range extension over the .308 Winchester for the 150 pound animal.

Now let's consider a heavier, 600 pound animal. The .308 is lethal against a 600 pound animal with 210 grain bullets up to only 250 yards, and the .300 Winchester Magnum is lethal on that size animal to 450 yards.



Game Weight	Bullet:	155	168	175	185	190	210
	Velocity:	3200	3074	3012	2929	2890	2749
		Maximum lethal range (yards)					
Game Weight	150 lb	825	875	925	1025	1075	1175
	300 lb	550	600	650	725	750	825
	600 lb	275	325	350	400	400	450

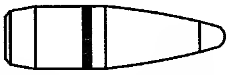
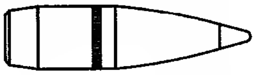
Figure 15.3. Effective lethal ranges for the entire line of .30 cal Berger VLD bullets for muzzle velocities typical of the .300 Winchester Magnum.

Once again I'll admit that this model does not account for the effects of shot placement. It's quite obvious that even a 155 grain bullet *can* kill a 600 pound animal at 1000 yards or more *if* the shot is placed in the animal's brain or spine. However the OGW model assumes nominal shot placement into the animal's chest cavity (heart/lung area). It's may not be responsible or fair to the animal to shoot at it with bullets that will strike with *below optimal energy* and cause a non-lethal wound (except in a few unlikely scenarios like a brain or spine hit). Bullet selection and shot ranges should be decided on with the assumption that you will be making nominal shots on the animal into its chest and the bullet should have sufficient energy to quickly and efficiently kill the animal with such a shot. This is the essence of the lethality charts based on Matunas' OGW formula.

We've examined how bullet weight and cartridge capacity affect the lethal range of a hunting rifle. Is there anything else that would affect the downrange energy that a bullet has available?

Long Range Lethality and the Ballistic Coefficient

Since the lethality of hunting bullets is so closely related to the energy and momentum of the bullet and these factors are both related to the velocity of the bullet, it's easy to understand that bullets which retain their velocity best will be more lethal at long range. The ballistic coefficient is a familiar measure of merit for external ballistic performance, but it's seldom thought of as being related to lethality. In fact, a high BC bullet has improved lethality for several reasons. First, the high sectional density which usually accompanies a high BC is a common measure of a bullet's penetration potential. Secondly, and more relevant to our current analysis is the fact that high BC bullets retain their velocity better at extended ranges and are therefore able to deliver greater energy to animals at extended range.

Bullet	**SD**	**i_7**	**G7 BC**	**G1 BC**
 *Hornady 150 BTSP*	0.226	1.309	0.173	0.337
 *Hornady 150 SST*	0.226	1.095	0.206	0.403

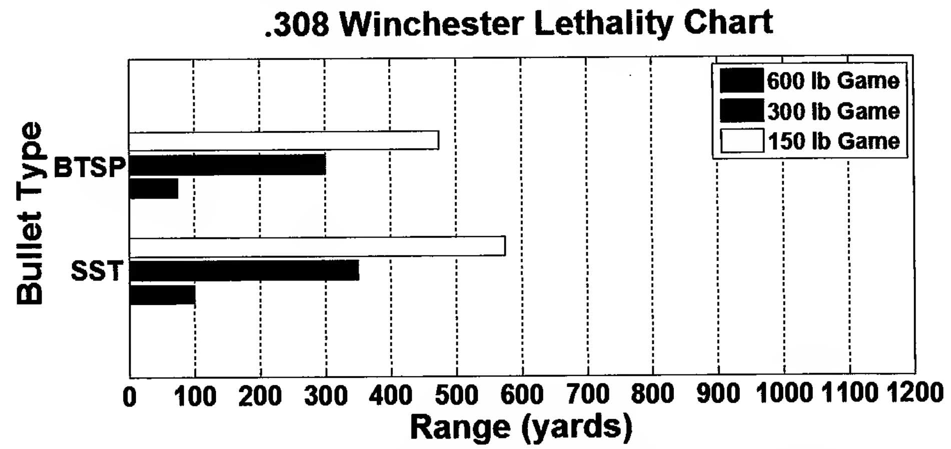


Figure 15.4. Two bullets of the same weight and caliber have the same sectional density. Due to the very different form factors, the SST has a significantly higher BC than the lead tipped bullet. The higher BC means the SST retains its energy better, and is lethal at a greater range.

Consider the two bullets in Figure 15.4. Since both bullets are the same caliber and weight they both have the same sectional density of 0.226 lb/in^2.

However, the longer ogive and the smaller tip diameter of the polymer tipped SST bullet give it significantly lower drag, and therefore a much higher BC. The G7 BC is 0.206 for the SST and only 0.173 for the lead tipped spire point. Let's see what effect that difference in BC has on the downrange lethality of these two bullets that have the same sectional density, and the same muzzle velocity.

Figure 15.4 shows the lethality advantage of a higher BC bullet. On large game, the lethal range is so short to begin with that the higher BC bullet barely has enough flight time to capitalize on its greater efficiency. The lethal range is only 25 yards longer for the higher BC bullet on 600 pound game (100 yards vs 75 yards). However, the range against a light animal is longer, which means the higher BC bullet will have a greater range over which to retain its velocity. As a result, it's able to *reach out* farther on smaller game that doesn't require as much bullet energy.

This concludes the development of bullet lethality for medium to heavy game. At the end of this chapter there are lethality charts presented for every bullet that I've tested for BC. The bullets are arranged by brand, and lethality charts are shown for each bullet from a small and large capacity cartridge. From these lethality charts you can determine the approximate maximum lethal range for each hunting bullet.

Let's review the major factors affecting lethality:

- The bullet's weight and striking velocity determine the kinetic energy and momentum that the bullet possesses. These properties determine the bullet's *potential* to do lethal damage.
- The bullet's weight is something you select, and has to do with the chosen caliber, whereas the bullet velocity is determined by cartridge selection *and* the range at which you're shooting.
- A high BC bullet retains velocity better and will be lethal at greater ranges compared to a lower BC bullet.

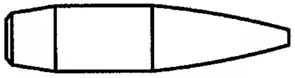
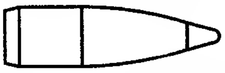
Optimal Game Weight for varmints

The Optimal Game Weight formula we've been working with applies to large animals, greater than 100 lb. Matunas also developed an Optimal Game Weight formula for varmints that's exactly the same as the big game formula with the exception of the constant used. Matunas' Optimal Game Weight Formula for varmints is:

$$OGW = V^3 W^2 \cdot 5 \times 10^{-13}$$

Again, V is velocity and W is bullet weight. Matunas' varmint formula uses the constant $5\text{x}10^{-13}$ instead of $1.5\text{x}10^{-12}$. All of the rules and limitations of the OGW Formula for big game apply for varmints as well.

One interesting contrast in varmint calibers is the comparison between the small capacity .223 Remington and the larger capacity .220 Swift. According to the previous analysis of .30 caliber bullets and big game, it would seem obvious that the larger capacity .220 Swift would be lethal on varmints at a greater range than the smaller .223 Remington. If *everything else were equal,* that would be the case, however, there is an important fact to consider regarding the .223 Remington. *It's very common for bolt action rifles that are chambered for the .223 Remington to have 1:9" twist barrels.* Larger capacity .22 caliber chamberings like the .220 Swift are usually made with 1:12" or 1:14" twist barrels. The significance of this fact is that the .223 Remington can stabilize longer heavier (higher BC) bullets than the .220 Swift with a slower twist barrel. I think the reason why the larger capacity .22 caliber cartridges use such slow twist rates is because hunters usually select them for maximizing velocity which is done with lighter bullets. Lighter bullets don't require a fast twist, and may even have trouble staying together at very high RPM. Figure 15.5 shows a lethality chart for a Nosler 55 grain Ballistic Tip fired from a .220 Swift at 3800 fps compared to a Berger 70 grain VLD from a .223 Remington at 2900 fps.

Bullet	SD	i_7	G7 BC	G1 BC
 *Berger 70 VLD*	0.199	1.050	0.190	0.371
 *Nosler 55 Ballistic Tip*	0.157	1.206	0.130	0.255

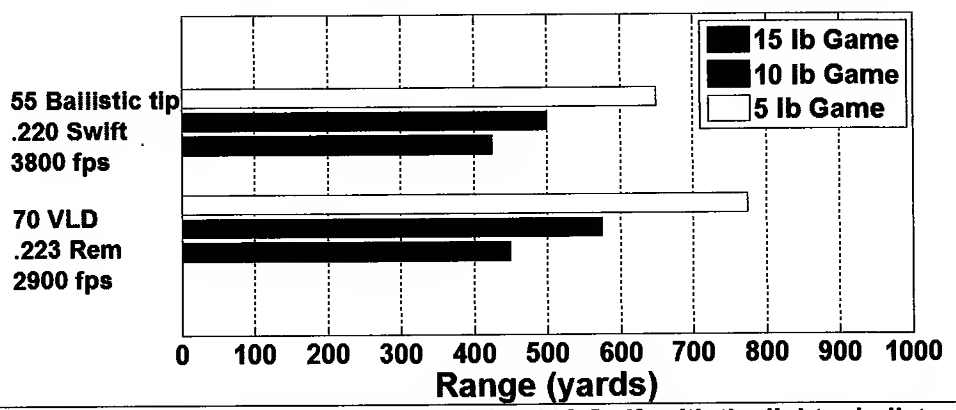


Figure 15.5 The high muzzle velocity of the .220 Swift with the lighter bullet results in a shorter lethal range than the .223 Remington with a higher BC bullet at a lower muzzle velocity.

Figure 15.5 shows a small advantage in lethal range for the slower, higher BC bullet compared to the faster, lower BC bullet. It's worth noting that the Berger 70 grain VLD is not classified as a varmint bullet, whereas the Nosler 55 grain ballistic tip is a varmint bullet of legendary notoriety. The point is that even though the OGW formula predicts an advantage for the .223

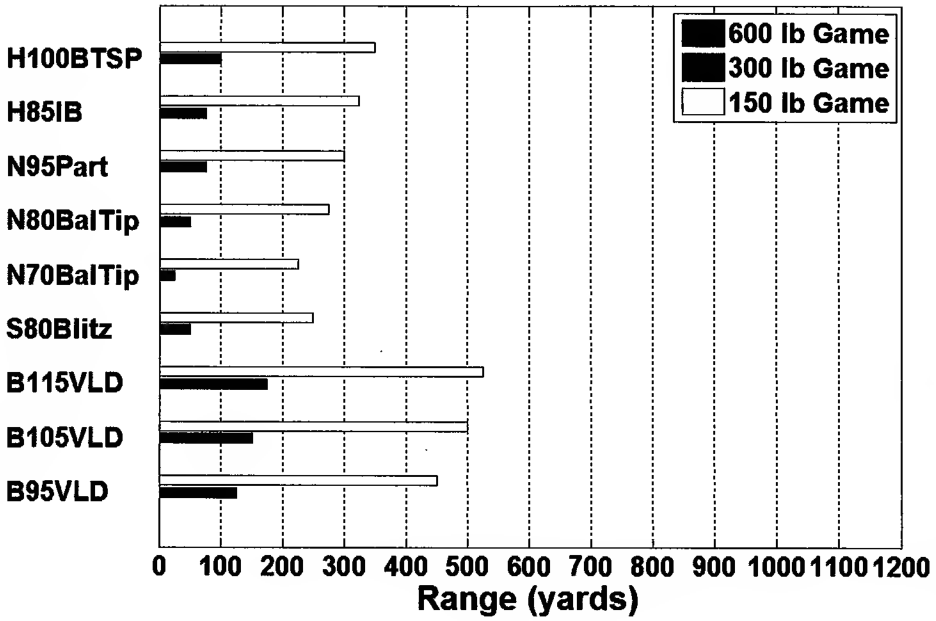
Remington using the 70 grain VLD, the fact is that the OGW formula doesn't take the bullet's construction and expansion into consideration. The Nosler Ballistic Tip can be expected to expand more dramatically than the Berger VLD, especially since this VLD is actually classified as a *target* bullet, not a varmint bullet. In the real world, the better terminal performance of the Ballistic Tip probably make up for the fact that it has less energy at range than the heavier bullet from the smaller cartridge. For very small varmints like prairie dogs that weigh less than 5 lb, even a non-expanding .22 caliber bullet will be quite lethal. When you get to larger varmints like fox and coyote that can weigh more than 10-15 lb, bullet construction starts to be a bigger issue.

The previous example shows in a roundabout way, *the rate of twist of a rifle barrel can have an impact on the rifles lethality* by enabling it to stabilize heavier bullets.

The remaining pages of this chapter will present lethality charts for several representative bullets in each caliber. The lethality charts are presented for all brands by caliber for velocities typical of medium and large capacity cases. The lethality charts can be used both as a guide line for selecting bullets for game, as well as comparing the effects of muzzle velocity and BC on a bullet's lethality. As is true in many parts of this book, the information about the *governing trends* are as valuable as the actual numbers themselves. Remember that the charts represent the extent of a bullets *optimal range*, not its absolute maximum lethal range. Shots taken outside the ranges shown in the charts can still be lethal, but will be less likely to deliver enough hydrostatic shock for an immediate incapacitation of the animal.

Many of the bullet brands and titles are abbreviated in the following tables in order to make them fit. For example, a Nosler 180 grain Ballistic Tip is shortened to Nos180BT or N180BT, etc.

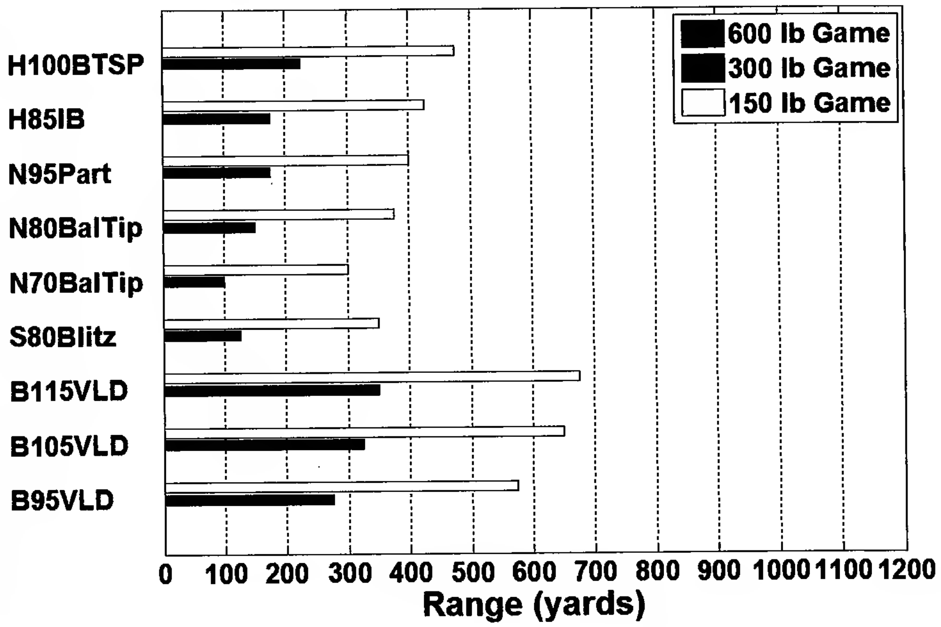
Lethality Chart for 6mm Medium Capacity Case
(Simlar to the 243 Winchester)



			Max Optimal Range		
Bullet	**BC**	**MV**	**150lb game**	**300lb game**	**600lb game**
Horn 100 BTSP	0.386	3000	350	100	0
Horn 85 Intbond	0.372	3254	325	75	0
Nosler 95 Part	0.345	3078	300	75	0
Nos 80 BallTip	0.323	3354	275	50	0
Nos 70 BallTip	0.279	3586	225	25	0
Sierra 80 Blitz	0.302	3354	250	50	0
Berger 115 VLD	0.551	2798	525	175	0
Berger 105 VLD	0.532	2928	500	150	0
Berger 95 VLD	0.486	3078	450	125	0

Figure 15.6

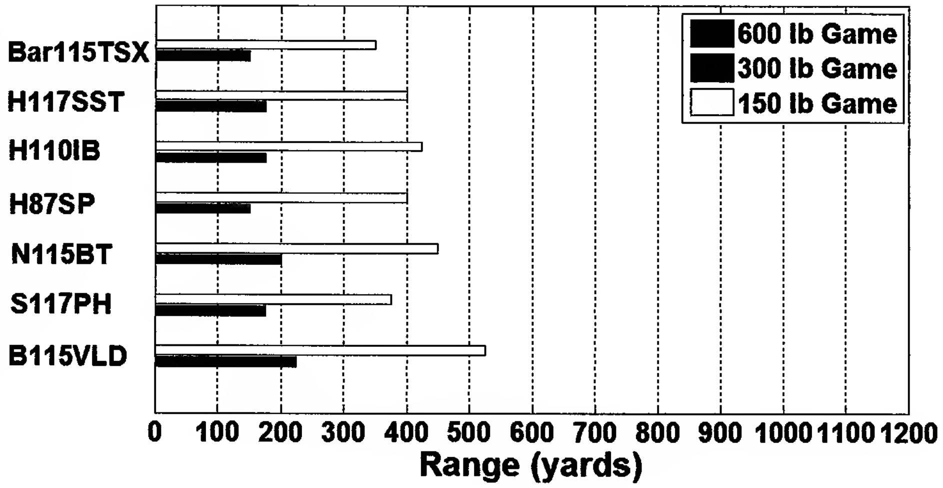
Lethality Chart for 6mm Large Capacity Case
(Similar to the 240 Weatherby Magnum)



			Max Optimal Range		
Bullet	BC	MV	150lb game	300lb game	600lb game
Horn 100 BTSP	0.386	3300	475	225	0
Horn 85 Intbond	0.372	3579	425	175	0
Nosler 95 Part	0.345	3386	400	175	0
Nos 80 BallTip	0.323	3690	375	150	0
Nos 70 BallTip	0.279	3944	300	100	0
Sierra 80 Blitz	0.302	3690	350	125	0
Berger 115 VLD	0.551	3077	675	350	0
Berger 105 VLD	0.532	3220	650	325	0
Berger 95 VLD	0.486	3386	575	275	0

Figure 15.7

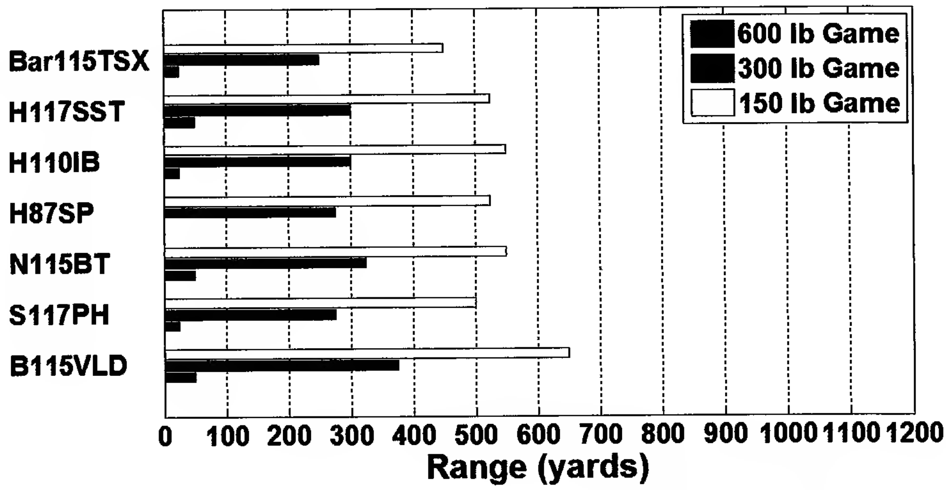
Lethality Chart for .257 caliber Medium Capacity Case
(Similar to .257 Roberts)



			Max Optimal Range		
Bullet	G7 BC	MV	150lb game	300lb game	600lb game
Barnes 115 TSX FB	0.164	2950	350	150	0
Hornady 117 SST	0.188	2925	400	175	0
Hornady 110 Intbnd	0.204	3016	425	175	0
Hornady 87 SP	0.149	3392	400	150	0
Nosler 115 Ball Tip	0.204	2950	450	200	0
Sierra 117 Pro Hnt	0.180	2925	375	175	0
Berger 115 VLD	0.239	2950	525	225	0

Figure 15.8

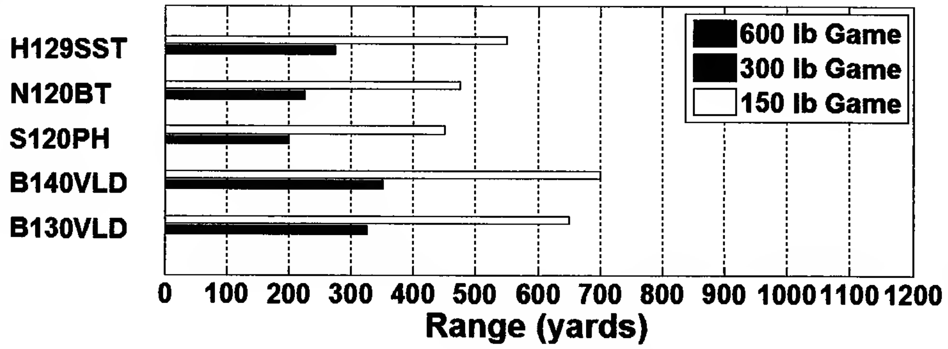
Lethality Chart for .257 caliber Large Capacity Case
(Similar to 257 Weatherby Magnum)



			Max Optimal Range		
Bullet	G7 BC	MV	150lb game	300lb game	600lb game
Barnes 115 TSX FB	0.164	3250	450	250	25
Hornady 117 SST	0.188	3222	525	300	50
Hornady 110 Intbnd	0.204	3323	550	300	25
Hornady 87 SP	0.149	3737	525	275	0
Nosler 115 Ball Tip	0.204	3250	550	325	50
Sierra 117 Pro Hnt	0.180	3222	500	275	25
Berger 115 VLD	0.239	3250	650	375	50

Figure 15.9

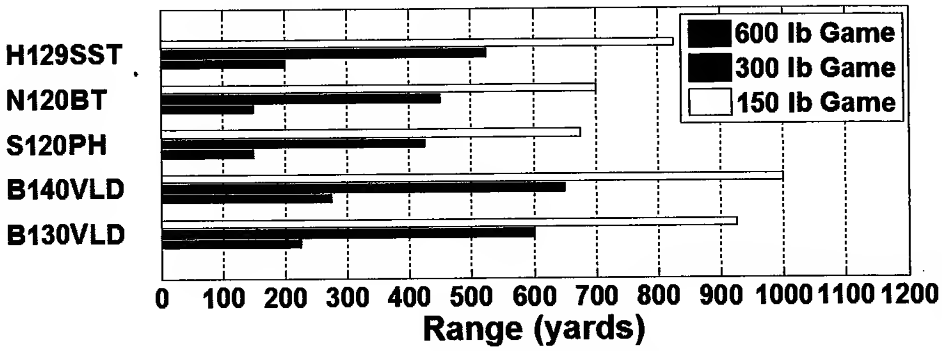
Lethality Chart for 6.5mm Medium Capacity Case
(Similar to 6.5mm x 55mm)



			Max Optimal Range		
Bullet	G7 BC	MV	150lb game	300lb game	600lb game
Horn 129 SST	0.247	2813	550	275	0
Nos 120 Ball Tip	0.214	2916	475	225	0
Sier 120 ProHunt	0.204	2916	450	200	0
Berger 140 VLD	0.313	2700	700	350	0
Berger 130 VLD	0.282	2802	650	325	0

Figure 15.10

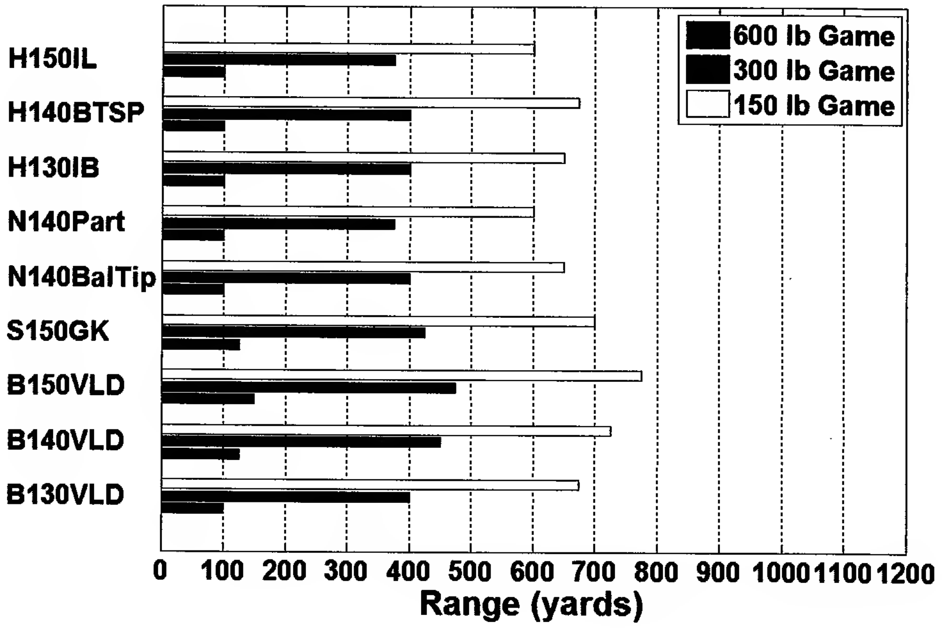
Lethality Chart for 6.5mm Large Capacity Case
(Similar to 264 Winchester Magnum)



			Max Optimal Range		
Bullet	**G7 BC**	**MV**	**150lb game**	**300lb game**	**600lb game**
Horn 129 SST	0.247	3334	825	525	200
Nos 120 Ball Tip	0.214	3456	700	450	150
Sier 120 ProHunt	0.204	3456	675	425	150
Berger 140 VLD	0.313	3200	1000	650	275
Berger 130 VLD	0.282	3321	925	600	225

Figure 15.11

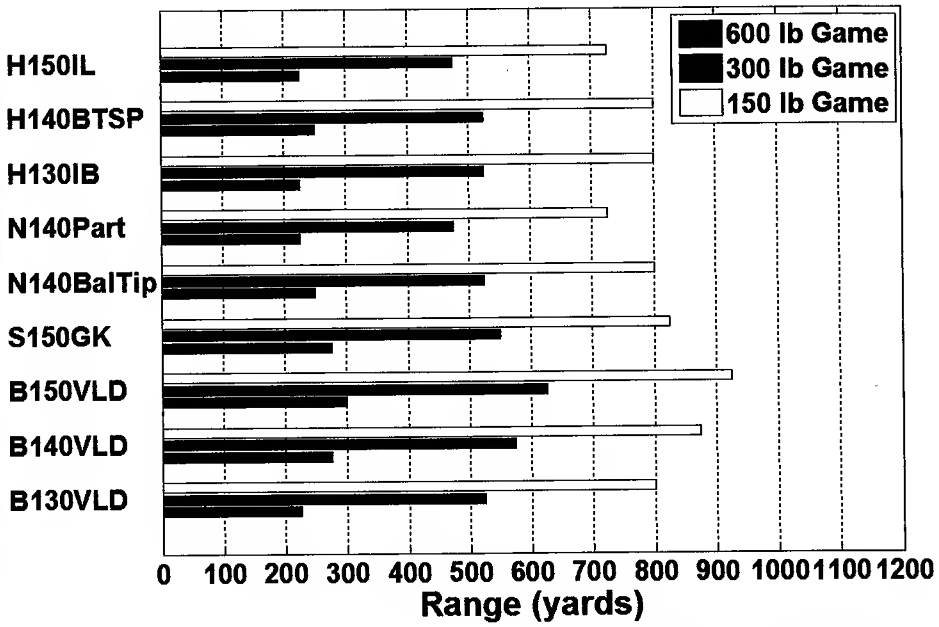
Lethality Chart for .277 Medium Capacity Case
(Similar to 270 Winchester)



			Max Optimal Range		
Bullet	G7 BC	MV	150lb game	300lb game	600lb game
Horn 150 IL	0.206	2898	600	375	100
Horn 140 BTSP	0.228	3000	675	400	100
Horn 130 IntBond	0.227	3113	650	400	100
Nosler 140 Part	0.207	3000	600	375	100
Nosler 140 BallTip	0.227	3000	650	400	100
Sier 150 GameKing	0.237	2898	700	425	125
Berger 150 VLD	0.263	2898	775	475	150
Berger 140 VLD	0.249	3000	725	450	125
Berger 130VLD	0.231	3113	675	400	100

Figure 15.12

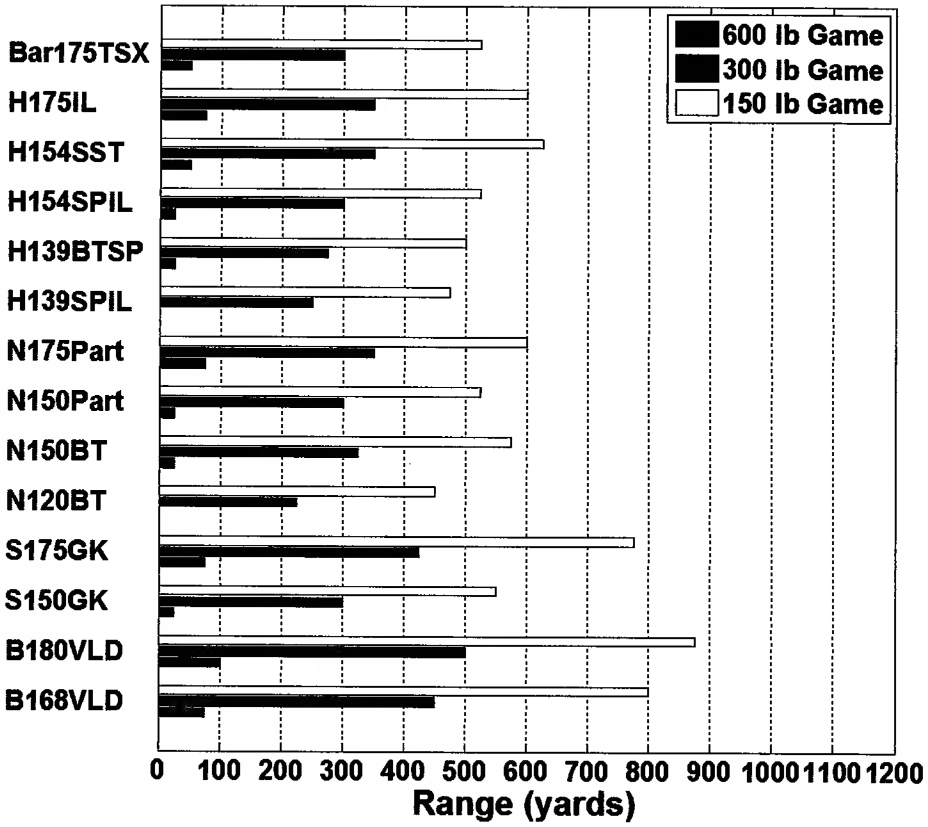
Lethality Chart for .277 Large Capacity Case
(Similar to 270 Weatherby Magnum)



Bullet	G7 BC	MV	Max Optimal Range 150lb game	300lb game	600lb game
Horn 150 IL	0.206	3188	725	475	225
Horn 140 BTSP	0.228	3300	800	525	250
Horn 130 IntBond	0.227	3425	800	525	225
Nosler 140 Part	0.207	3300	725	475	225
Nosler 140 BallTip	0.227	3300	800	525	250
Sier 150 GameKing	0.237	3188	825	550	275
Berger 150 VLD	0.263	3188	925	625	300
Berger 140 VLD	0.249	3300	875	575	275
Berger 130VLD	0.231	3425	800	525	225

Figure 15.13

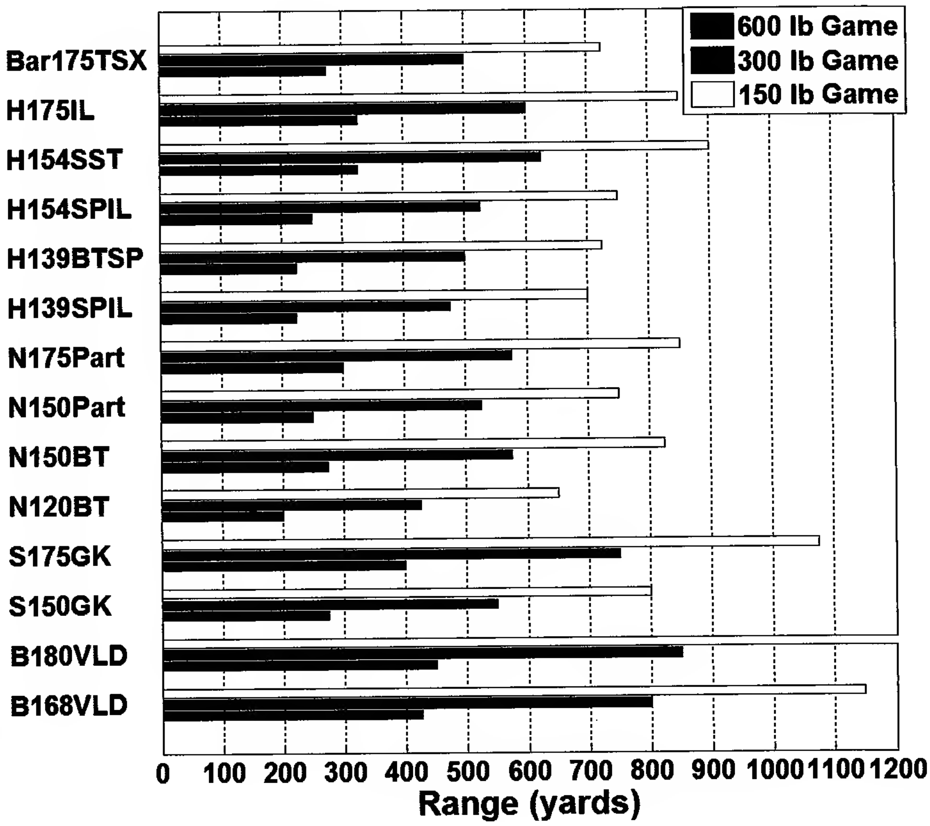
Lethality Chart for 7mm Medium Capacity Case
(Similar to 7mm-08)



			Max Optimal Range		
Bullet	G7 BC	MV	150lb game	300lb game	600lb game
Bar 175 TSX	0.203	2500	525	300	50
Horn 175 IL	0.236	2500	600	350	75
Horn 154 SST	0.251	2665	625	350	50
Horn 154 SPIL	0.210	2665	525	300	25
Horn 139 BTSP	0.204	2805	500	275	25
Horn SPIL	0.196	2805	475	250	0
Nos 175 Part	0.232	2500	600	350	75
Nos 150 Part	0.212	2700	525	300	25
Nos 150 BallTip	0.229	2700	575	325	25
Nos 120 BallTip	0.185	3019	450	225	0
Sier 175 GK	0.296	2500	775	425	75
Sier 150 GK	0.220	2700	550	300	25
Berger 180 VLD	0.337	2465	875	500	100
Berger 168 VLD	0.316	2552	800	450	75

Figure 15.14

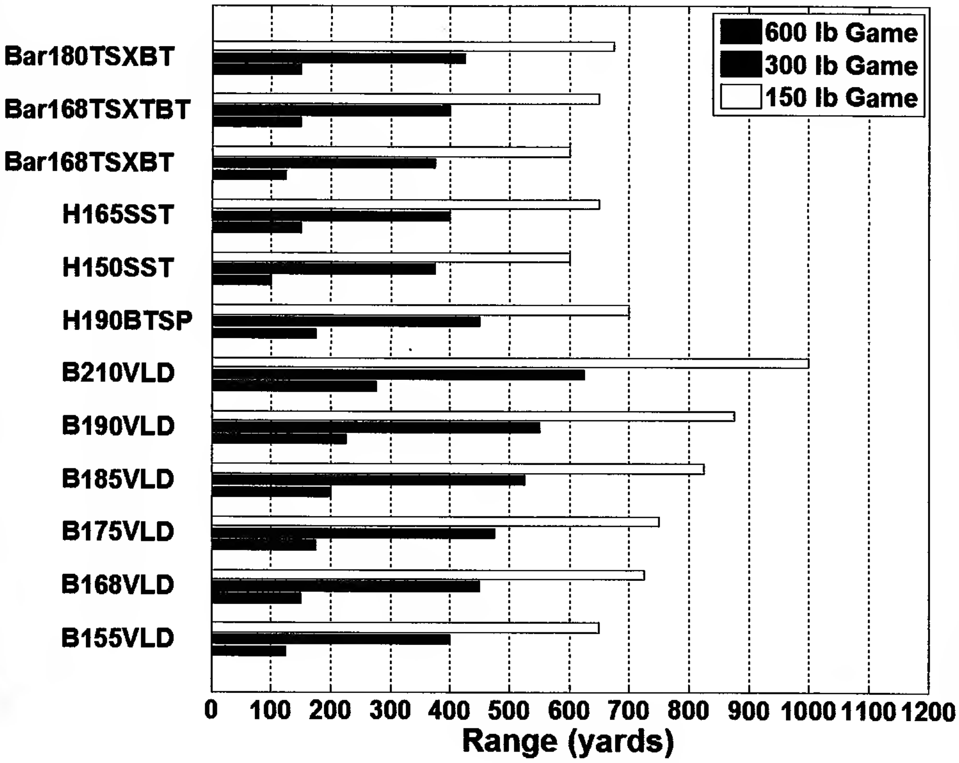
Lethality Chart for 7mm Large Capacity Case
(Similar to 7mm Remington Magnum)



			Max Optimal Range		
Bullet	G7 BC	MV	150lb game	300lb game	600lb game
Bar 175 TSX	0.203	3000	725	500	275
Horn 175 IL	0.236	3000	850	600	325
Horn 154 SST	0.251	3198	900	625	325
Horn 154 SPIL	0.210	3198	750	525	250
Horn 139 BTSP	0.204	3366	725	500	225
Horn SPIL	0.196	3366	700	475	225
Nos 175 Part	0.232	3000	850	575	300
Nos 150 Part	0.212	3240	750	525	250
Nos 150 BallTip	0.229	3240	825	575	275
Nos 120 BallTip	0.185	3623	650	425	200
Sier 175 GK	0.296	3000	1075	750	400
Sier 150 GK	0.220	3240	800	550	275
Berger 180 VLD	0.337	2958	1225	850	450
Berger 168 VLD	0.316	3062	1150	800	425

Figure 15.15

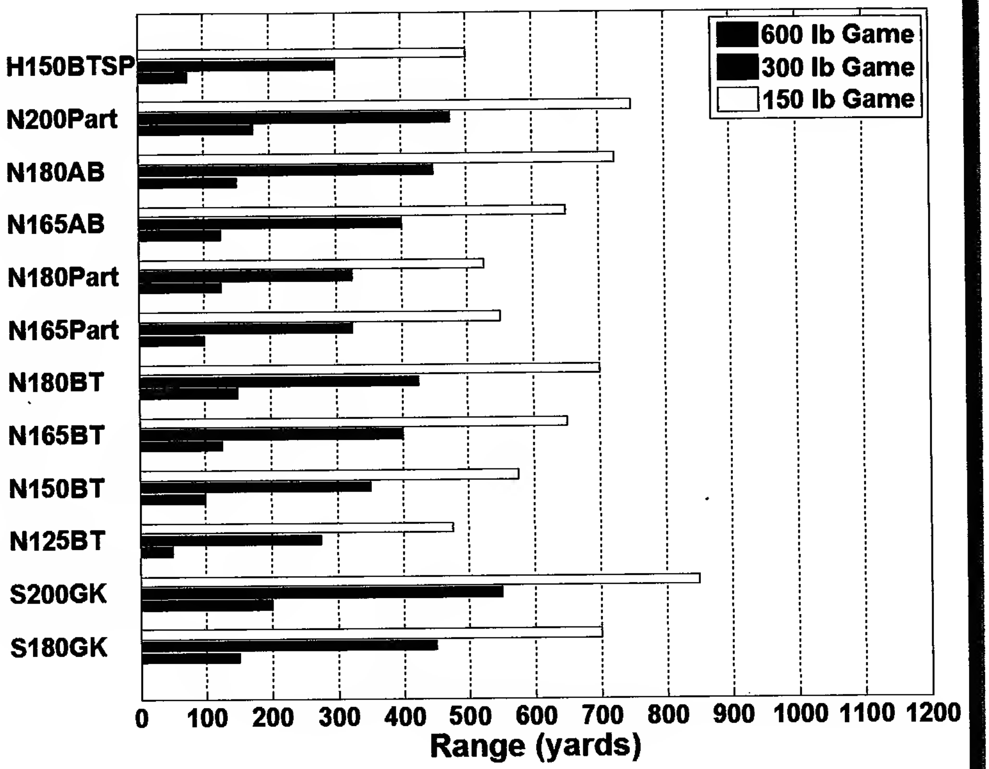
Lethality Chart for 30 Caliber Medium Capacity Case
(Similar to .308 Winchester)



			Max Optimal Range		
Bullet	G7 BC	MV	150lb game	300lb game	600lb game
Bar 180 TSX BT	0.229	2645	675	425	150
Bar 168 TSXBT	0.222	2738	650	400	150
Bar 168 TSXTBT	0.207	2738	600	375	125
Horn 165 SST	0.224	2762	650	400	150
Horn 150 SST	0.206	2897	600	375	100
Horn 190 BTSP	0.238	2574	700	450	175
Berger 210 VLD	0.323	2449	1000	625	275
Berger 190 VLD	0.291	2574	875	550	225
Berger 185 VLD	0.281	2609	825	525	200
Berger 175 VLD	0.255	2682	750	475	175
Berger 168 VLD	0.242	2738	725	450	150
Berger 155 VLD	0.225	2850	650	400	125

Figure 15.16

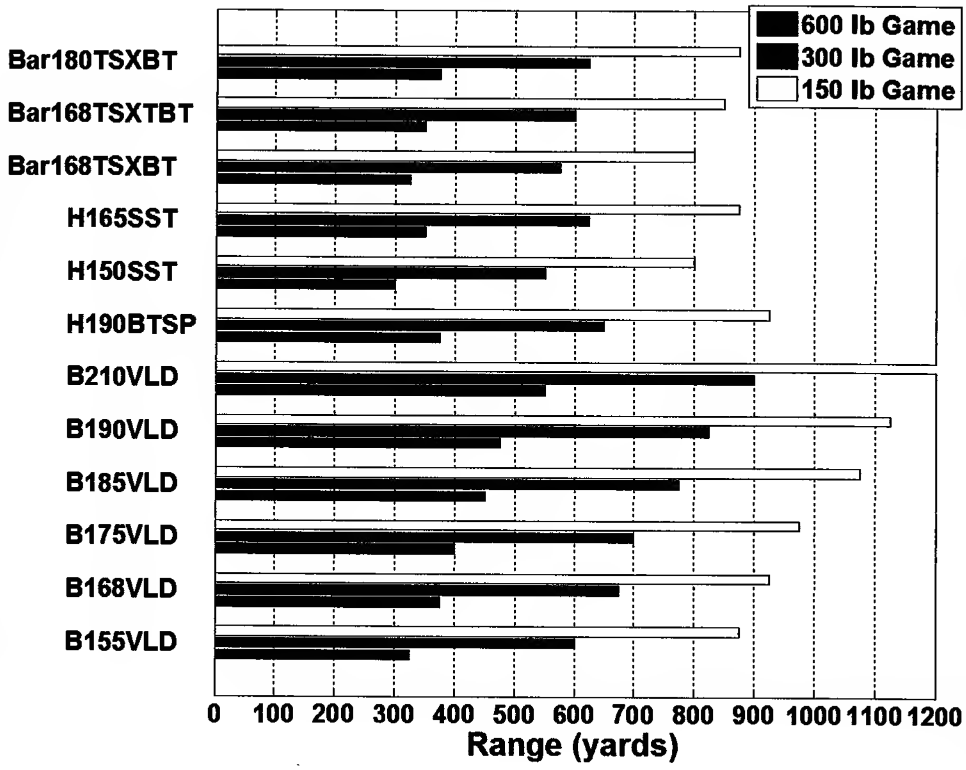
Lethality Chart for 30 Caliber Medium Capacity Case (cont.)
(Similar to .308 Winchester)



			Max Optimal Range		
Bullet	G7 BC	MV	150lb game	300lb game	600lb game
Horn 150 BTSP	0.173	2897	500	300	75
Nos 200 Part	0.250	2509	750	475	175
Nos 180 AcBond	0.246	2645	725	450	150
Nos 165 AcBond	0.228	2762	650	400	125
Nos 180 Part	0.184	2645	525	325	125
Nos 165 Part	0.188	2762	550	325	100
Nos 180 BallTip	0.241	2645	700	425	150
Nos 165 BallTip	0.227	2762	650	400	125
Nos 150 BallTip	0.203	2897	575	350	100
Nos 125 BallTip	0.167	3174	475	275	50
Sier 200 GK	0.290	2509	850	550	200
Sier 180 GK	0.242	2645	700	450	150

Figure 15.17

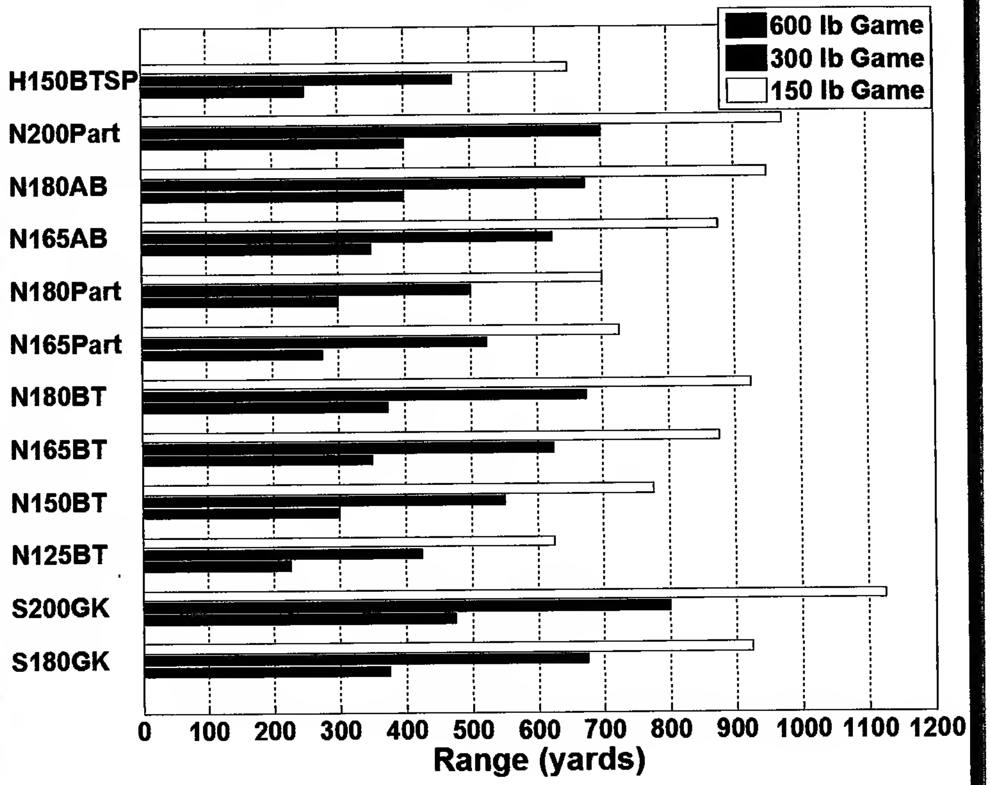
Lethality Chart for 30 Caliber Large Capacity Case
(Similar to 300 Weatherby Magnum)



			Max Optimal Range		
Bullet	G7 BC	MV	150lb game	300lb game	600lb game
Bar 180 TSX BT	0.229	3082	875	625	375
Bar 168 TSXBT	0.222	3190	850	600	350
Bar 168 TSXTBT	0.207	3190	800	575	325
Horn 165 SST	0.224	3219	875	625	350
Horn 150 SST	0.206	3376	800	550	300
Horn 190 BTSP	0.238	3000	925	650	375
Berger 210 VLD	0.323	2854	1275	900	550
Berger 190 VLD	0.291	3000	1125	825	475
Berger 185 VLD	0.281	3040	1075	775	450
Berger 175 VLD	0.255	3126	975	700	400
Berger 168 VLD	0.242	3190	925	675	375
Berger 155 VLD	0.225	3321	875	600	325

Figure 15.18

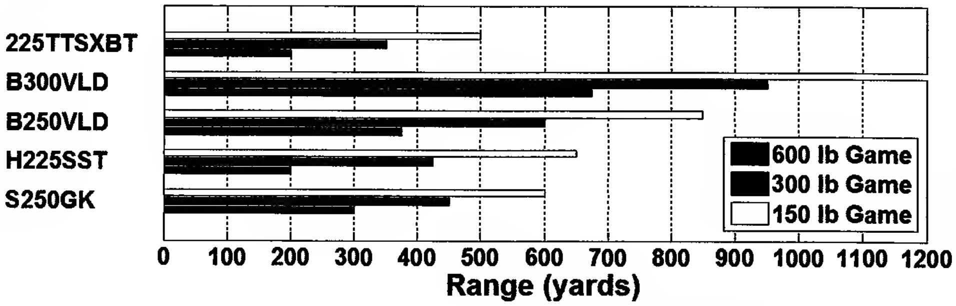
Lethality Chart for 30 Caliber Large Capacity Case (cont.)
(Similar to 300 Weatherby Magnum)



			Max Optimal Range		
Bullet	G7 BC	MV	150lb game	300lb game	600lb game
Horn 150 BTSP	0.173	3376	650	475	250
Nos 200 Part	0.250	2924	975	700	400
Nos 180 AcBond	0.246	3082	950	675	400
Nos 165 AcBond	0.228	3219	875	625	350
Nos 180 Part	0.184	3082	700	500	300
Nos 165 Part	0.188	3219	725	525	275
Nos 180 BallTip	0.241	3082	925	675	375
Nos 165 BallTip	0.227	3219	875	625	350
Nos 150 BallTip	0.203	3376	775	550	300
Nos 125 BallTip	0.167	3699	625	425	225
Sier 200 GK	0.290	2924	1125	800	475
Sier 180 GK	0.242	3082	925	675	375

Figure 15.19

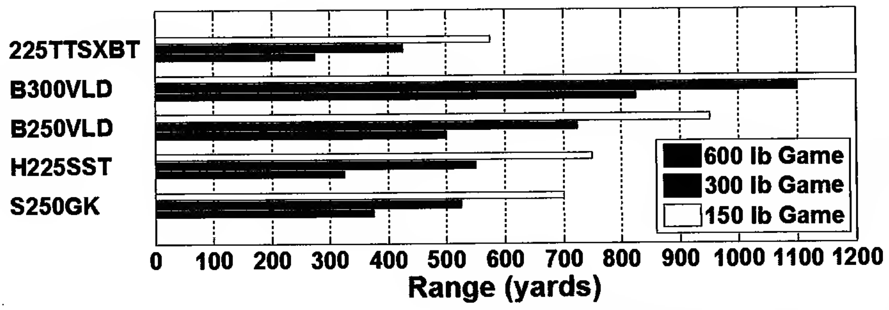
Lethality Chart for .338 caliber Medium Capacity Case
(Similar to .338-06)



			Max Optimal Range		
Bullet	**G7 BC**	**MV**	**150lb game**	**300lb game**	**600lb game**
Bar 225 TTSXBT	0.253	2846	500	350	200
Berger 300 VLD	0.468	2465	1275	950	675
Berger 250 VLD	0.390	2700	850	600	375
Horn 225 SST	0.381	2846	650	425	200
Sier 250 GK	0.266	2700	600	450	300

Figure 15.20

Lethality Chart for .338 caliber Large Capacity Case
(Similar to .338 Lapua Magnum)



			Max Optimal Range		
Bullet	**G7 BC**	**MV**	**150lb game**	**300lb game**	**600lb game**
Bar 225 TTSXBT	0.253	3162	575	425	275
Berger 300 VLD	0.468	2738	1425	1100	825
Berger 250 VLD	0.390	3000	950	725	500
Horn 225 SST	0.381	3162	750	550	325
Sier 250 GK	0.266	3000	700	525	375

Figure 15.21

Chapter 16: Weapon Employment Zone Analysis

The Weapon Employment Zone (WEZ) analysis method is a way of figuring out your hit percentage. There are two basic reasons why you might want to know your hit percentage:

1) So that you can know if a shot is a *high confidence* or *low confidence* shot given your rifle system and field uncertainties.
2) So that you can do ballistic performance analyses to determine how to best improve your equipment and *increase* your hit percentage in a given application.

It's great that ballistics can provide us with accurate fire solutions (windage and elevation). That's always been sort of the classic role of ballistics in long range shooting. However, WEZ analysis and the ability to figure out your hit percentage is another powerful way to use the science of ballistics to make judgments about your equipment and individual shots.

The following introductory segment will outline the analysis method used throughout this lengthy chapter. If you're interested in the WEZ analysis method, you can read a more extensive treatment of the topic in the book: *Accuracy and Precision for Long Range Shooting* **[REF 11].**

WEZ analysis is a systematic and comparative evaluation of small arms performance. WEZ analysis is model based, statistical in nature, and quantifies the *hit percentage* of a given shooting system on specified targets as a function of range. This analysis is carried out using defined uncertainties related to practical field shooting.

Uncertainties and Confidence Levels

In a WEZ analysis, shooter skill and environmental variables are modeled to illustrate the effect on a weapon systems ability to hit a target amidst realistic field conditions. This is important because uncertainties are inevitable in field shooting and any good analysis should account for their presence and show how a rifles' hit percentage is affected by the uncertainties.

Environmental uncertainties primarily include range and wind estimation. The WEZ analysis can be run with a pre-determined *confidence set* which is a set of variables characterized by high, medium or low confidence. The following table represents pre-determined confidence sets chosen to reflect uncertainty levels in shooter skill and equipment capability.

	Confidence		
	High	**Medium**	**Low**
Wind Estimation	+/- 1 mph	+/- 2.5 mph	+/- 4 mph
Range Estimation	+/- 1 yard	+/- 10 yards	+/- 50 yards
Rifle Precision	0.5 MOA	1.0 MOA	1.5 MOA
Velocity Consistency	10 fps SD	15 fps SD	20 fps SD

Table 16.1. The uncertainty levels chosen to represent high, medium and low confidence enable *apples-to-apples* comparisons among weapon systems in given environments.

The cross wind and range estimation are related to how well skilled and equipped the shooter is. For example, the most elite shooters may be able to judge cross wind speed within +/- 1 mph[22] in an environment having good indicators. However, a novice wind reader in a difficult environment may struggle to get within +/- 4 mph.

The range estimation error is defined as +/- 1 yard for the high confidence scenario. This is consistent with a shooter using a laser rangefinder on a reflective target, within the operational range of the device. A medium confidence range uncertainty of +/- 10 yards represents expert use of a ranging reticle, or the use of a laser rangefinder on a non-reflective target, perhaps at the limits of the rangefinders operational range. A low confidence range uncertainty of +/- 50 yards is used to characterize the average use of ranging reticles, or straight estimation.

The rifle/ammo precision is represented by group sizes of 0.5 MOA, 1.0 MOA or 1.5 MOA for high, medium and low confidence levels, respectively. These are the average group sizes that the rifle/shooter are capable of at close range.

The variation in Muzzle Velocity (MV) of the ammunition is characterized by Standard Deviation (SD). The high confidence scenario characterizes MV variation as having a SD of 10 fps. This is typically only achievable by carefully hand-loaded ammunition. 15 fps SD represents the medium confidence scenario. This SD is consistent with good quality factory produced ammunition. 20 fps SD is considered low confidence/low consistency, and is representative of low quality factory ammo.

When performing a WEZ analysis, a full confidence set can be specified according to Table 16.1, or the elements can be mixed. For example, you can look at a WEZ for a system that has high confidence cross wind and range estimation, medium confidence rifle/ammo precision, and low confidence velocity consistency for the ammo. In this way, the WEZ can be used to illustrate how much the systems hit percentage might be improved by addressing the various uncertainty components. Said differently, this analysis approach can show what element(s) of the environment or shooter/rifle system is most limiting to the systems' ability to hit targets.

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[22] Uncertainties represent the 95% confidence intervals assuming a normal distribution. In other words, if the uncertainty in range is cited as +/- 1 yard, it means the standard deviation of range error is 0.5 yards. The simulation will model a bell curve of range error with 67% of the estimates being within +/- 0.5 yards (+/- 1σ) and 95% of the estimates being within +/- 1.0 yards (+/- 2σ).

Of course it's possible to specify uncertainty levels other than those listed in Table 16.1. However, one of the major benefits of WEZ analysis is the ability to compare shooting systems using the *same* criteria. In this case, the point is to compare the relative performance of systems under the *same conditions*. By mixing and matching the uncertainty elements of Table 16.1 to suite a specific scenario, you would lose the ability to compare systems in standard environments.

Using the WEZ analysis, it is also possible to study the effects of various ballistics related problems like; inconsistency in a bullets' Ballistic Coefficient (BC), rifle cant, uncertainty in uphill/downhill look angle, etc. Furthermore, problems of *accuracy* can be studied to determine their effect on hit percentage as well as precision effects (accuracy is addressed in a later section).

Modeling

The WEZ analysis consists of running a ballistics program[23] repeatedly with the user specified field uncertainties. Each individual trajectory is modeled with a different set of inputs, randomly selected from a normal distribution within the defined uncertainty bounds. For precision studies, the center of the group is corrected to the center of the target, and each trajectory modeled will either hit the target or not based on dispersion. For analysis involving effects of inaccuracy, the center of the group can be offset from the center of the target.

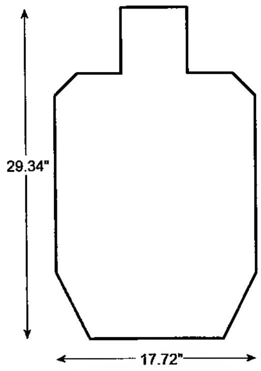

Figure 16.1. IPSC target. Dimensions in inches.

If the simulation is run 100 times and the specific field uncertainties result in 80 hits and 20 misses, then the result is a 80% hit percentage at that range, against that target, under those specific conditions. In reality, the simulation is run 1,000 times to insure a more repeatable result. Since the WEZ approach is statistical, absolute repeatability is not guaranteed, but large sample sizes foster greater repeatability[24].

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[23] The ballistics program used for this analysis is a version of the Applied Ballistics Point Mass Solver, specifically tailored to loop within the given uncertainty parameters. This solver uses a 1000 Hz Runge-Kutta numerical method to solve the equations of aero-ballistic motion.

[24] With 1,000 shots, hit percentage typically repeats within 1% or 2%.

Naturally the hit percentage for a given weapon system depends on the target. Any target shape can be used including circles, squares, etc. For the following example, the IPSC silhouette target shown in Figure 16.1 is used to model WEZ. Other size targets are defined in later analysis.

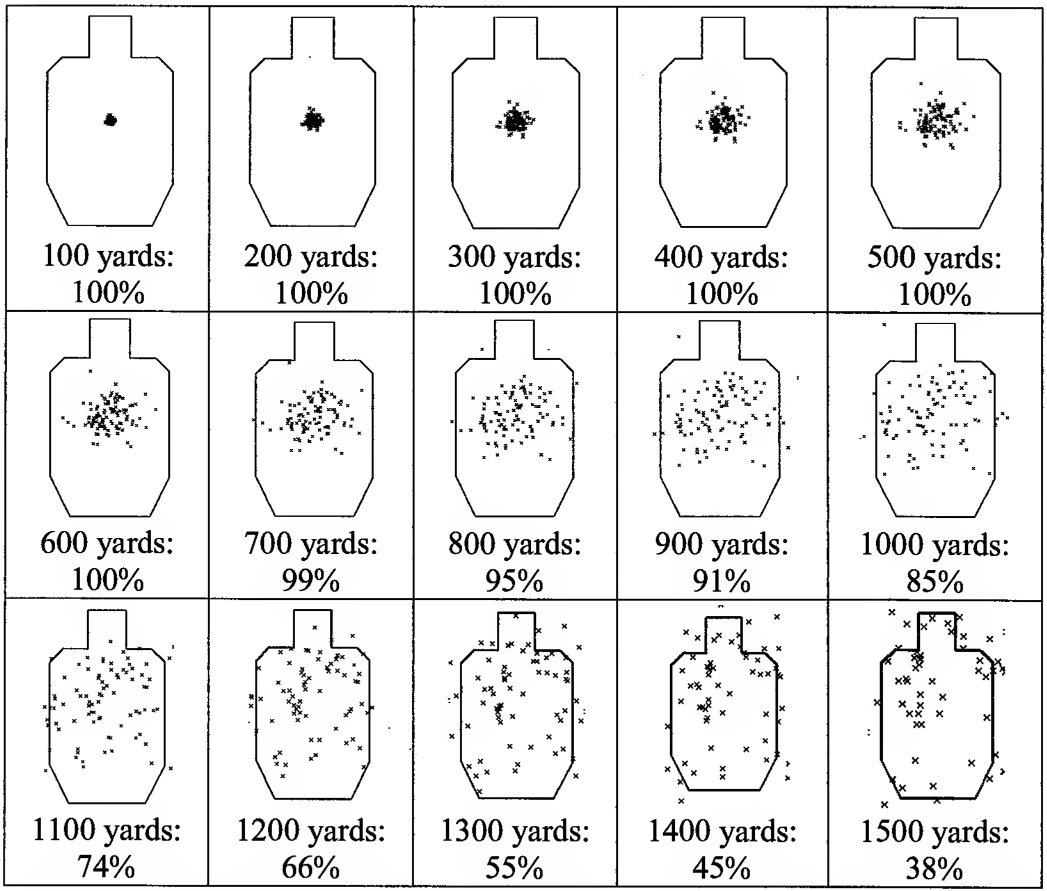
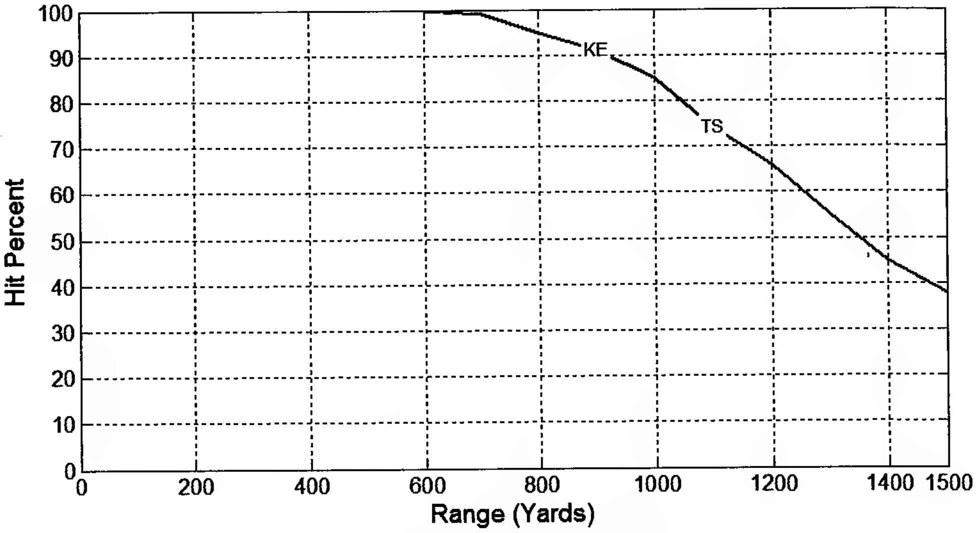

100 yards: 100%
200 yards: 100%
300 yards: 100%
400 yards: 100%
500 yards: 100%
600 yards: 100%
700 yards: 99%
800 yards: 95%
900 yards: 91%
1000 yards: 85%
1100 yards: 74%
1200 yards: 66%
1300 yards: 55%
1400 yards: 45%
1500 yards: 38%

Figure 16.2. As the range increases, more and more shots miss the target and the hit percentage decreases. As this Figure clearly shows, any WEZ analysis is highly dependent on the chosen target size and shape.

Figure 16.2 shows graphically the result of running a 100 shot WEZ analysis for a sample rifle against the IPSC silhouette target from 100 to 1500 yards. Exact details are not important to this conceptual demonstration, only the hit-or-miss criteria is being demonstrated. Note that hit percentage remains 100% until the range is long enough that uncertainties result in some trajectories missing the target, at which point the hit percentage falls off to less than 100%, bottoming out to 38% at 1500 yards.

The plot on the following page shows this same type of information, condensed into a single range-based hit percentage. In actual analysis reports, Figure 16.3 is the more practical format to consider WEZ results. Figure 16.2 is only shown to demonstrate the conceptual nature of how the hit percentage is determined.

Example WEZ Plot

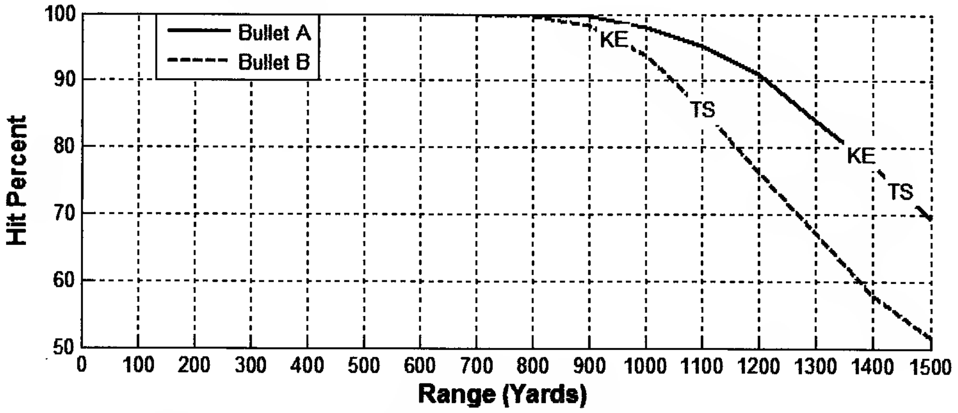


Range	Hit Percentage
100	100%
200	100%
300	100%
400	100%
500	100%
600	100%
700	99%
800	95%
900	91%
1000	85%
1100	74%
1200	66%
1300	55%
1400	45%
1500	38%

Figure 16.3. This plot and table shows the hit percentage as a function of range. This is the same information gathered by the method illustrated in Figure 16.2, but in a more practical, analytical form.

In addition to showing the hit percentage and how it drops off with range, the WEZ plot in Figure 16.3 also marks where critical transonic (TS) and kinetic energy (KE) values are reached. The merit of KE as a measure of importance is debatable, but the TS range is an important landmark range due to the effects of transonic instability that's possible with many bullets and the difficulty in predicting trajectories beyond that range.

High Confidence Environment WEZ: Example Comparison



Criteria: This WEZ was run for a high confidence environment:

Wind determination: +/- 1.0 mph
Range determination: +/- 1.0 yards
Rifle/Ammo precision: 0.5 MOA
Velocity consistency: 10 fps SD

Range Yards	Bullet A	Bullet B
100	100%	100%
200	100%	100%
300	100%	100%
400	100%	100%
500	100%	100%
600	100%	100%
700	100%	100%
800	100%	100%
900	100%	98%
1000	98%	94%
1100	95%	86%
1200	91%	76%
1300	84%	67%
1400	78%	58%
1500	69%	52%

Figure 16.4. Hit percentage comparison between two bullets in similar high confidence scenario. Note the hit percentage numbers shown in gray are associated with ranges beyond the transonic (TS) range of the projectile.

In other words, when a projectile falls below TS speed, depending on the particular bullet and atmospherics, it may become unstable and tumble which renders the trajectory unpredictable and ineffective beyond that point. Hit percentages that extend beyond the TS range will appear in grey to indicate the overwhelming uncertainties of transonic performance on the WEZ modeling. When hit probabilities appear in grey, they can be interpreted as being between that number and zero.

Of course there is great value in quantifying the hit percentage of a given rifle/ shooter/ ammo combination in a specific uncertainty environment. That information can be used to quantify sniper effectiveness in war-gaming scenarios, or help a hunter decide on what range should be considered maximum for a certain game he's hunting in that environment. However there is another very useful application of the WEZ analysis, and that is the *comparison of several weapon systems under the same conditions*. Is a .300 Winchester Magnum more capable with a medium weight 190 grain bullet, or higher BC but slower 220 grain bullet? How does a 10% BC increase affect hit percentage? How much is hit percentage improved by training a shooter to judge cross wind to within +/- 2 mph as opposed to +/- 4 mph? Is the investment in more consistent ammo worth the gains in hit percentage? How is the hit percentage of a given weapon system affected by going from a sea level environment to 10,000 feet above sea level? Are resources better spent on new rifles, or better ballistic software, or more training? The answers to these and many other important questions can be answered with WEZ analysis. Ultimately, the WEZ analysis can be used to optimize system design for maximum hit percentage in given environments with known uncertainty levels.

Figure 16.4 compares hit percentage for two different bullets being loaded into the same cartridge, in the same uncertainty environment. Bullet A is a heavy, high BC, slower MV bullet. Bullet B is a light weight, lower BC but higher MV option. It's clear in Figure 16.4 that in this specific high confidence environment, both Bullets A and B maintain a 100% hit percentage out to 800 yards. Beyond 800 yards, Bullet A has a higher hit percentage. We can also see from the WEZ plot that Bullet A (heavier, higher BC, lower MV) maintains supersonic speed out to 1450 yards, where Bullet B only reaches 1100 yards before dropping below transonic speed.

Keep in mind that the results from this example are specific to the uncertainties under which the WEZ was run. If the same comparison were made under different conditions; for example if the range uncertainty were great, then Bullet B might be the better option due to being faster and flatter over short/medium range. This result exemplifies the old adage: use the right tool for the job. Just because Bullet A is clearly the right tool for this specific job (uncertainty set) doesn't mean it's universally the right choice in all uncertainty sets. In fact it is very likely that there will be a different set of circumstances in which Bullet B could be superior to Bullet A, and the WEZ analysis would show that.

Accuracy vs. Precision in WEZ Analysis

The system of WEZ analysis presented so far only addresses the effects of *precision* related problems. In other words, the ballistic calculations and sight corrections are assumed to be perfect, resulting in the group being centered on the target. However in real life this is rarely the case.

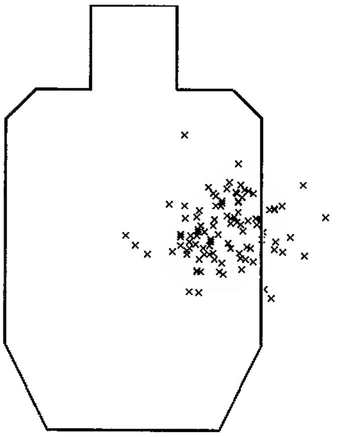


Figure 16.5. WEZ analysis can also quantify how hit percentage suffers with imperfect accuracy.

Other interesting WEZ studies can be done to look at the effects of errors in trajectory prediction and other inaccuracies on hit percentage. In other words, errors that will cause a shot group to not be centered on the point of aim. For example, uncertainty in ballistic program inputs including; average muzzle velocity, average BC, BC vs. custom drag curve, sight height, atmospheric temperature, pressure and humidity, even the consequences of not accounting for Coriolis and spin drift can be determined by a WEZ analysis. This type of WEZ analysis would be looking at *accuracy* as opposed to (or in addition to) *precision* limitations of weapon employment.

Precision analysis deals with shot-to-shot variations which cause dispersion in a shot group. Accuracy analysis considers errors that will offset the group center from the intended aim point.

There are many interesting analyses to consider. Figure 16.5 illustrates a situation where a weapon system has sufficient *precision* to achieve 100% hit percentage, but due to the *inaccuracy* of the group (not being centered), the hit percentage is much less than 100%.

WEZ analyses that focus on precision related variables will be relevant to equipment performance, meaning the precision of the rifle as well as consistency and ballistic performance of the ammunition. On the contrary, WEZ analysis that focuses on accuracy will apply to the shooters training and proper employment of ballistic predictions.

Limitations

There are things which are important to a weapons overall effectiveness that can't be captured in the WEZ analysis. For example, differences in barrel life for various rifle/ammo combinations. Another issue is terminal ballistic performance. Related things like this can be addressed through discussion because they won't necessarily show up in the hit percentage tables.

Summary of methodology

A thorough and careful WEZ analysis can guide decisions as to which weapon systems and shooting skills are most effective at maximizing hit percentage in certain environments and confidence scenarios. The approach can also serve as a sensitivity analysis to determine which variables have the greatest effect on hit percentage, considering limitations of *precision* and/or *accuracy*. Ultimately, the WEZ approach to analyzing hit percentage for small arms can be used to optimize weapon system design and training objectives for strategically maximizing hit percentage in general, or in specific environments.

The methodology described in this chapter is used to illustrate various points about accuracy and precision. The WEZ/hit percentage analysis is the framework and context that we'll use to discuss the influence of many individual variables. Learning to process all the uncertainties involved in long range shooting from this *effects* based analysis will help in determining the reasons why we miss targets. Identifying the cause of failure is a necessity on the road to success.

Example WEZ Calculation

The 308 Winchester is a very common round, well known by many shooters so it makes sense to use it as a case study. Let's see what the hit percentages are for some common scenarios. We'll look at the hit percentages for various target sizes, under different uncertainty environments. Remember everything in Part 1 is a *precision* analysis, meaning it's assumed that the group is centered on the aim point. Later in Part 2, we'll revisit this analysis while considering *accuracy* as well as *precision.* In other words, what happens to hit percentage if the fire solution is not perfect, and the group is not centered?

Modeling: Rifle and Ammunition

For this analysis, we'll be modeling the 175 grain SMK at 2600 fps. This bullet/velocity is typical of the M24 rifle (Remington 700 with a 24" barrel) and M118LR ammunition.

M24 Sniper Weapon System

Bullet	G7 BC	Muzzle Velocity (24" barrel)
175 SMK	0.243	2600 fps

Figure 16.6. M24 Sniper Weapon System.

Note that even if this isn't your exact rifle and ammo type, the analysis will still be relevant to any .308 Winchester shooting middle weight bullets, even if the numbers don't work out exactly the same.

The 175 grain SMK is well known for its accuracy, reliability, and transonic stability. All of these attributes make it a good bullet to consider for this analysis. Figure 16.7 shows a dimensioned drawing of the 175 SMK.

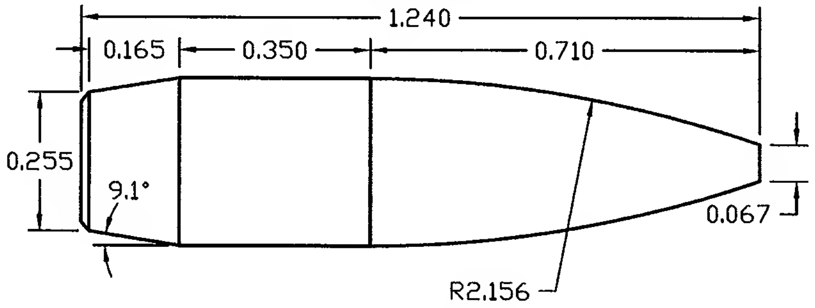

Sierra 175 grain MatchKing

Figure 16.7. The 175 grain Sierra MatchKing. A common long range bullet used in M118LR ammunition.

Modeling: Shooter, Environment, and Target

Now that the rifle and ammo have been established, we turn to the shooter and environments that will be modeled in this analysis. When looking at hit percentage calculations for a rifle system, it's important to consider the various elements that will affect the employment of that weapon including the shooters skill, and the quality of the equipment. These variables will be characterized by the high, medium, and low confidence environments shown in Table 16.2.

	Confidence		
	High	**Medium**	**Low**
Cross Wind Estimation	+/- 1 mph	+/- 2.5 mph	+/- 4 mph
Range Estimation	+/- 1 yard	+/- 10 yards	+/- 50 yards
Rifle/Ammo Precision	0.5 MOA	1.0 MOA	1.5 MOA
Velocity Consistency	10 fps SD	15 fps SD	20 fps SD

Table 16.2. The uncertainty levels chosen to represent high, medium and low confidence environments.

Notice that the attributes which make up the high confidence scenario represent a high level of shooter skill. The ability to estimate wind within +/- 1 mph is very rare, and some might argue impossible in certain conditions (A well trained, experienced shooter can do it in easy conditions). The +/- 1 yard of range estimation is really just assuming that the shooter is making use of a laser rangefinder. The 1/2 MOA short range precision of the rifle/ammo is attributed to the rifle and shooters marksmanship. Finally the 10 fps of standard deviation in muzzle velocity is considered very good; nearly impossible by factory ammo standards, and acceptable for most hand loaders. Parameters of the medium and low confidence environment are also given in Table 16.2.

We'll model hit percentage against several targets in this analysis. Primarily the IPSC silhouette target shown in Figure 16.8.

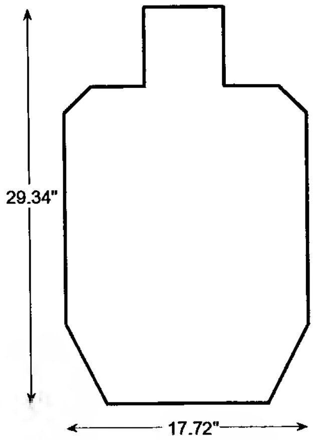


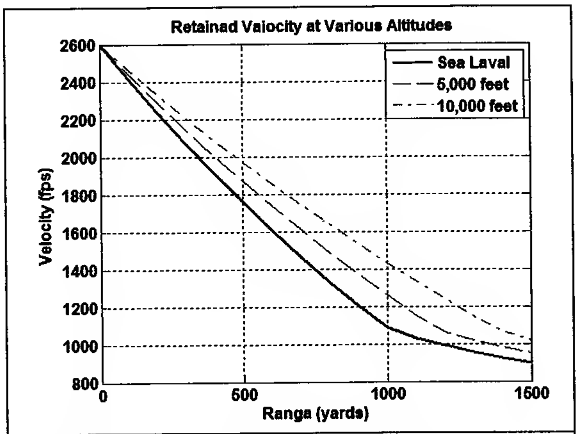
Figure 16.8. IPSC target. Dimensions in inches.

It should be no surprise that hit percentage is greatly affected by the size and shape of the target being shot at. All else equal, the larger the target, the greater the hit percentage.

In addition to the IPSC silhouette target (humanoid shape) which is only relevant for military applications, we'll also look at round targets of various diameters. The round targets will be sized in a fixed number of inches, rather than being a certain 'MOA'. Often times shooters talk about hitting certain 'MOA' sized targets at various ranges (1 MOA is roughly 5" at 500 yards, 10" at 1000 yards, etc.). Although this is a common practice, it's not conducive to hit percentage analysis against certain sized targets. In other words, a deer has a vital zone which is the same size no matter if the deer is 500 or 1000 yards from you. You care about your ability to hit that vital zone, not hitting a certain MOA sized target.

Retained Velocity at Various Altitudes

The first analysis we will consider is the effect of environment on retained velocity. Many people don't realize the important effect that air density has on ballistic performance. Air density is 15% less at 5000 feet altitude than at sea level. This has the same effect as shooting a bullet with 15% higher BC at sea level. Needless to say, that 15% can make a big difference in performance, so it's worth exploring.



Range (Yards)	Retained Velocity (fps)		
	Sea Level	5,000 ft	10,000 ft
Muzzle	2600	2600	2600
500	1758	1869	1970
1000	1089	1259	1431
1500	896	951	1016

Figure 16.9. Dramatic effect of altitude on retained velocity.

Figure 16.9 shows graphically the difference in retained velocity for 5,000 ft increments in altitude, or density altitude (DA). At just 500 yards, the 5,000 foot retained velocity is already 110 fps greater than the sea level case. At 1000 yards, there's 170 fps difference, and 342 fps difference from sea level to 10,000 feet. These velocities are particularly significant because they're transonic. Transonic speed is important because the aerodynamics and stability of a bullet are less predictable at this speed. The transonic point in the velocity traces can be seen above as a *knee* in the curve. For the sea level case, the bullet passes thru the speed of sound very close to 1000 yards. At 5,000 feet, the range is extended to over 1200 yards, and for the 10,000 foot scenario, the bullet just barely slows to the speed of sound at 1500 yards. Note the *knee* in the velocity curve is indicating the bullet passing thru the actual speed of sound (1116 fps at sea level), but *transonic effects* are a factor from around 1339 fps down to 893 fps (1.2 and 0.8 times the speed of sound).

Of course hit percentage is the primary objective of this analysis, not retained velocity. However as we'll see, retained velocity affects hit percentage, therefore *altitude affects hit percentage.*

Hit Percentage at Various Altitudes

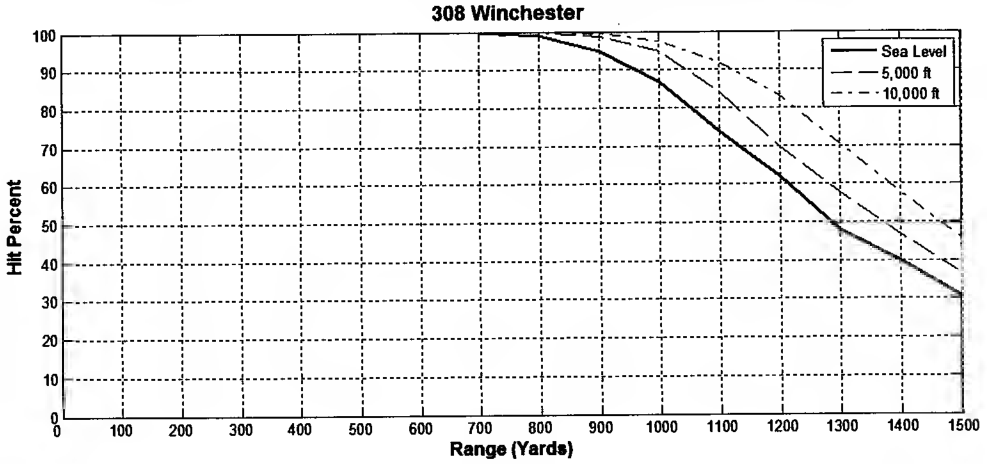
Figure 16.10 sums up the results of the 308 Winchester's hit percentage at various altitudes with M118LR ammunition on the IPSC target in a *high confidence* environment.

There are many interesting things to observe about the results in Figure 16.10. First is that the hit percentage is dramatically affected by altitude, as our velocity retention analysis indicated. For example, the hit percentage at 1000 yards increases from 87% at sea level to 95% at 5,000 feet, and to 98% at 10,000 feet. By 1200 yards, the difference in hit percentage is maximized. The 5,000 foot hit percentage is 70%, which is 8% higher than the sea level hit percentage of 62%. Then the 10,000 foot altitude hit percentage is another 13% higher yet. Altogether, *by going from sea level to 10,000 feet, the hit percentage of this system is increased by 21%!*

This is valuable information for military strategists to take into consideration when deploying to different theaters around the world. For example, much of Afghanistan is located at high altitude and long lines of sight are very common. That combination of increased weapon effectiveness and open battlefields make long range shooting a much more effective tactic than many other theaters in the world.

If you think these numbers look optimistic based on your experience, remember that they represent the high confidence environment which is basically the best case scenario; 0.5 MOA rifle and shooter, 10 fps standard deviation, +/- 1 mph of wind uncertainty, and near perfect range measurement. For a look at a more realistic or average scenario, consider the medium confidence environment hit percentages shown in Figure 16.11.

Different Altitudes in a High Confidence Environment



Criteria

This WEZ was run for a high confidence set of environmental variables including the following:

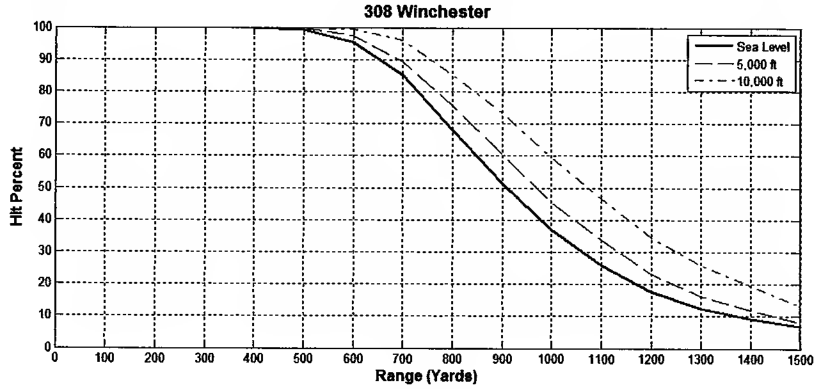
Wind determination: +/- 1.0 mph
Range determination: +/- 1.0 yards
Rifle/Ammo precision: 0.5 MOA
Velocity consistency: 10 fps SD

Range Yards	Sea Level	5,000 feet	10,000 feet
100	100%	100%	100%
200	100%	100%	100%
300	100%	100%	100%
400	100%	100%	100%
500	100%	100%	100%
600	100%	100%	100%
700	100%	100%	100%
800	99%	100%	100%
900	95%	99%	100%
1000	87%	95%	98%
1100	74%	84%	92%
1200	62%	70%	83%
1300	48%	58%	71%
1400	40%	47%	58%
1500	31%	37%	46%

Figure 16.10. Hit percentage comparison in high confidence scenario. Note the hit percentage numbers shown in gray are associated with ranges beyond the transonic (TS) range of the projectile (below 1339 fps).

Figure 16.11 tells a much different tale about hit percentage. In the high confidence environment, 100% hit percentage was carried out to 700 yards at sea level, and 900 yards at 10,000 feet. However in the medium confidence environment, 100% hit percentage only carries to 400 yards at sea level and 600 yards at 10,000 feet.

Different Altitudes in a Medium Confidence Environment



Criteria

This WEZ was run for a medium confidence set of environmental variables including the following:

Wind determination: +/- 2.5 mph
Range determination: +/- 10 yards
Rifle/Ammo precision: 1.0 MOA
Velocity consistency: 15 fps SD

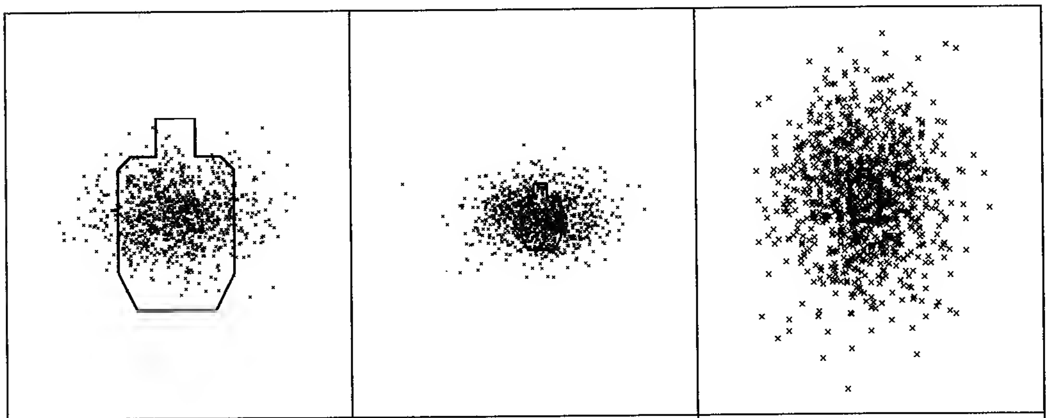
Range Yards	Sea Level	5,000 feet	10,000 feet
100	100%	100%	100%
200	100%	100%	100%
300	100%	100%	100%
400	100%	100%	100%
500	99%	100%	100%
600	96%	98%	100%
700	85%	89%	96%
800	68%	76%	85%
900	51%	61%	73%
1000	37%	46%	60%
1100	26%	34%	47%
1200	18%	23%	35%
1300	12%	16%	26%
1400	9%	12%	19%
1500	7%	8%	13%

Figure 16.11. Hit percentage comparison in medium confidence scenario. Note the hit percentage numbers shown in gray are associated with ranges beyond the transonic (TS) range of the projectile (below 1339 fps).

The more dramatic effects of the confidence environment are evident at longer ranges. By 1000 yards, the hit percentage in a medium confidence environment has fallen to 37% at sea level, 46% at 5,000 feet, and 60% at 10,000 feet. At 1500 yards, hit percentages are dismal, falling to the 7% to 13% range.

There are certain ranges over which altitude effects will be most prevalent for the different confidence environments. Looking at the high confidence environment, hit percentage is affected by about 20% from roughly 1100 to 1400 yards due to altitude effects. However in a medium confidence environment, the hit percentage is still affected 20% by altitude effects, but the effect occurs in a shorter range window; from 800 to 1200 yards. In the low confidence environment, altitude affects hit percentage by 15%, and the range window is around 500-800 yards. The conclusion to be drawn here is that *altitude affects hit percentage more at* *__shorter ranges__* *for* *__lower confidence__* *environments and longer ranges for higher confidence environments.*

Note that in the low confidence environment, hit percentage drops below 100% at 400 yards at all altitudes. The uncertainties in wind, range, etc. are just too much and the trajectories disperse so much that by 700 yards, hit percentages are approaching 50% at all altitudes.



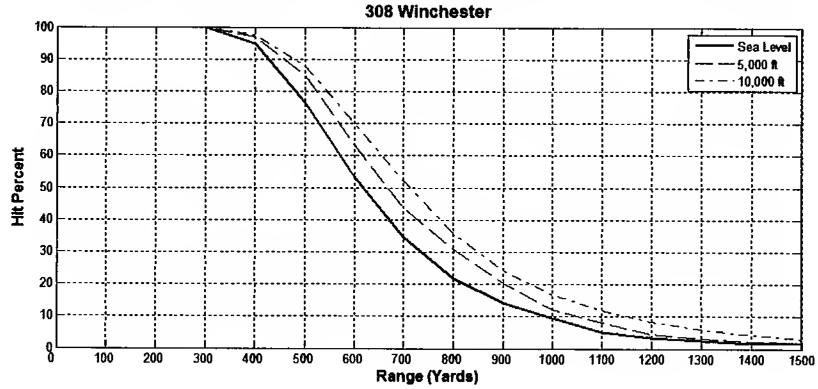
High Confidence 87% Hit Percentage	Medium Confidence 37% Hit Percentage	Low Confidence 9% Hit Percentage

Figure 16.12. Dispersion at 1000 yards for various confidence environments at sea level.

It's important to keep in mind when considering lower hit percentages that this is where the computer model is least certain. The computer simulates 1000 shots, counts the hits, and calculates the percentage. The problem with simulating a low confidence environment is that the data scatter is great enough that back-to-back computer runs don't always produce the same hit percentage. This is mostly a problem for low confidence environments, and at the very low hit percentages, which tend to be the less important parts of the WEZ analysis.

Figure 16.12 shows the shot scatter for the 308 Winchester at 1000 yards, sea level, for high, medium and low confidence environments.

Different Altitudes in a Low Confidence Environment



Criteria

This WEZ was run for a low confidence set of environmental variables including the following:

Wind determination: +/- 4.0 mph, Range determination: +/- 50 yards

Rifle/Ammo precision: 1.5 MOA, Velocity consistency: 20 fps SD

Range Yards	**Sea Level**	**5,000 feet**	**10,000 feet**
100	100%	100%	100%
200	100%	100%	100%
300	100%	100%	100%
400	95%	97%	98%
500	77%	85%	88%
600	54%	64%	70%
700	35%	44%	52%
800	22%	31%	36%
900	14%	20%	24%
1000	9%	12%	17%
1100	5%	8%	12%
1200	3%	5%	8%
1300	3%	3%	6%
1400	2%	2%	4%
1500	2%	2%	3%

Figure 16.13. Hit percentage comparison in low confidence scenario. Note the hit percentage numbers shown in gray are associated with ranges beyond the transonic (TS) range of the projectile (below 1339 fps).

Note that in the high confidence environment, there are no shots that disperse beyond the vertical extent of the target. In other words the major cause for missing is windage. For the medium confidence environment, the majority of the dispersion is due to windage. In the low confidence environment where range is estimated within +/-50 yards, the primary dispersion is vertical, which even overwhelms the +/- 4 mph of wind uncertainty.

Figure 16.13 shows a plot and table of the hit percentage as a function of range for 3 different altitudes.

Effects of Various Target Sizes on Hit Percentage

So far all of the analysis on the .308 Winchester in various confidence environments and altitudes has been based around the IPSC target. What if your target is something else? What if you're a hunter interested in hit % on deer or elk sized vital zones? The hit percentage analysis can easily be adapted to apply to any size or shape of target.

To prevent the analysis from becoming too complicated, the remainder of this chapter will focus only on sea level standard conditions. We'll consider the 3 confidence environments on 5", 10" and 15" circular targets shown in comparison to the IPSC target in Figure 16.14.

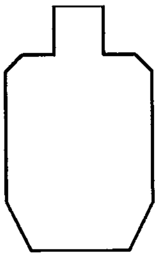
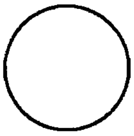
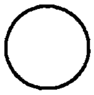
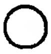
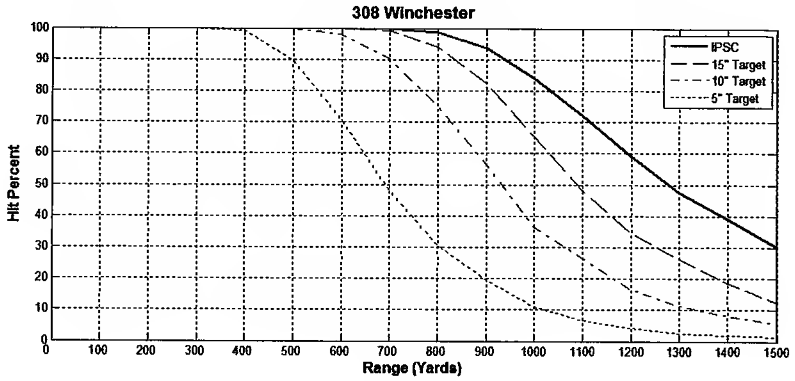
			
IPSC	15" circle	10" circle	5" circle
Suitable for modeling:			
Humanoid shaped targets	Vital zones for large game like elk, moose, etc.	Vital zones for medium game like deer.	Vital zones for (larger) varmints and predators.

Figure 16.14. Four different target sizes used to model hit probability for various classes of targets.

When the computer simulation is run for various sized targets, the 1000 trajectories are modeled only once, and then the different targets are assessed for their hit %. In other words, the same data set that's used to generate hit percentage on the IPSC silhouette is used against the 15", 10" and 5" targets. This insures valid *comparisons* of hit percentage for the various targets.

The following figures show the hit percentage for the .308 Winchester, 175 grain SMK, and the 4 different target sizes at sea level in high, medium and low confidence environments.

Variable Targets in a High Confidence Environment



Criteria

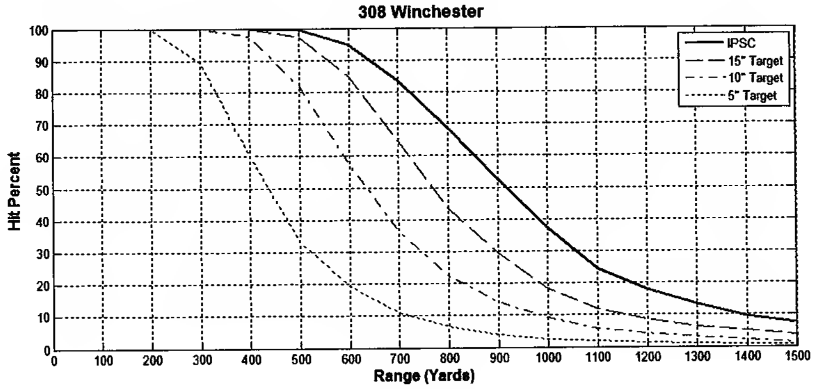
This WEZ was run for a high confidence set of environmental variables including the following:

Wind determination: +/- 1.0 mph
Range determination: +/- 1 yards
Rifle/Ammo precision: 0.5 MOA
Velocity consistency: 10 fps SD

Range Yards	IPSC	15" Target	10" Target	5" Target
100	100%	100%	100%	100%
200	100%	100%	100%	100%
300	100%	100%	100%	100%
400	100%	100%	100%	99%
500	100%	100%	100%	90%
600	100%	100%	98%	71%
700	100%	99%	90%	48%
800	99%	94%	75%	31%
900	94%	82%	56%	19%
1000	84%	65%	36%	11%
1100	72%	48%	27%	7%
1200	59%	35%	17%	4%
1300	47%	26%	11%	3%
1400	39%	19%	8%	2%
1500	30%	12%	6%	1%

Figure 16.15. Hit percentage for high confidence environment against various size targets at sea level.

Variable Targets in a Medium Confidence Environment



Criteria

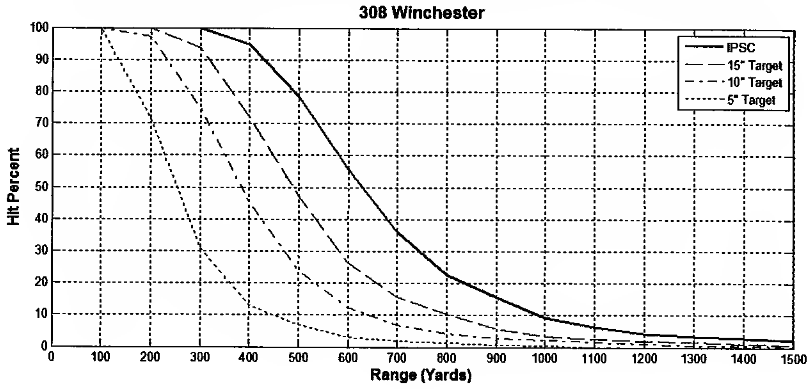
This WEZ was run for a medium confidence set of environmental variables including the following:

Wind determination: +/- 2.5 mph
Range determination: +/- 10 yards
Rifle/Ammo precision: 1.0 MOA
Velocity consistency: 15 fps SD

Range Yards	IPSC	15" Target	10" Target	5" Target
100	100%	100%	100%	100%
200	100%	100%	100%	100%
300	100%	100%	100%	89%
400	100%	100%	97%	60%
500	100%	97%	82%	33%
600	95%	85%	58%	19%
700	83%	65%	37%	11%
800	69%	44%	23%	7%
900	53%	29%	14%	4%
1000	37%	18%	9%	3%
1100	25%	12%	6%	2%
1200	18%	9%	4%	1%
1300	13%	6%	3%	1%
1400	10%	5%	2%	1%
1500	8%	4%	1%	1%

Figure 16.16. Hit percentage for medium confidence environment against various size targets at sea level.

Variable Targets in a Low Confidence Environment



Criteria

This WEZ was run for a low confidence set of environmental variables including the following:

Wind determination: +/- 4 mph
Range determination: +/- 50 yards
Rifle/Ammo precision: 1.5 MOA
Velocity consistency: 20 fps SD

Range Yards	IPSC	15" Target	10" Target	5" Target
100	100%	100%	100%	100%
200	100%	100%	97%	72%
300	100%	94%	75%	31%
400	95%	72%	46%	13%
500	78%	47%	24%	7%
600	56%	27%	13%	3%
700	36%	16%	7%	2%
800	23%	11%	4%	1%
900	16%	6%	3%	1%
1000	9%	3%	2%	0%
1100	6%	2%	2%	0%
1200	4%	2%	1%	0%
1300	3%	2%	1%	0%
1400	3%	1%	0%	0%
1500	2%	1%	0%	0%

Figure 16.17. Hit percentage for low confidence environment against various size targets at sea level.

Notice how dramatically the hit percentages fall off for the smaller sized targets. This should not be a surprise due to the much reduced surface area.

The hit percentage on the 5" target is 0% beyond 900 yards in the low confidence environment. This is due largely to the fact that the rifle/ammo/shooter groups only 1.5 MOA at best, which is almost 15" groups at that range. Add to that the effects of 20 fps SD in muzzle velocity, +/-50 yards uncertainty in range, and +/- 4 mph of wind uncertainty and it's clear that hitting the 5" circle approaches statistical impossibility.

If you were using this rifle and ammunition on a deer hunt (where the vital area is roughly 10") in a medium confidence environment, and you only wanted to take shots where your change of hitting was 90% or better, your range would be limited to about 450 yards. If you practiced your shooting (improved group size), loaded more consistent ammunition, improved wind reading and range measurements, you might be able to push that out to 700 yards (high confidence environment). However, that could be wishful thinking because remember this analysis only looks at precision elements of hit percentage and assumes perfect accuracy. In other words, the hit percentages reported here assume the shot groups are perfectly centered on the target, and that misses only occur due to imperfect precision (meaning groups bigger than the target).

Long range hunting scenarios sometimes allow for accuracy to be fine-tuned before actually shooting at an animal. Sometimes you can take a couple of practice shots on a rock or other inanimate object while waiting for a shot at an animal. Any error in the fire solution would be reduced and the hunter would have higher confidence in shot placement when an animal appears near that location. Doing this would improve your *accuracy*, but you could still miss due to lack of *precision* (group size being too big). Remember, to hit small targets at long range you need both *accuracy* *and* *precision.* In other words, you have to be able to center your group, as well as shoot a small group.

Summary of WEZ methodology

This section presented an example WEZ analysis for the .308 Winchester case for various certainty environments, altitudes, and target sizes. The results are summarized below.

- The effect of altitude on retained velocity is dramatic, and performance is heavily dependent on velocity retention.
- A given % reduction in air density is equivalent to the same % increase in BC.
- Going up in altitude increases hit percentage for all confidence environments. The effect can be on the order of 10% increase in hit percentage for every 5000 feet above sea level.
- Altitude affects hit percentage at longer ranges for high confidence environments, and shorter range for lower confidence environments.

- Target size also plays a tremendous role in hit percentage with differences being more dramatic at longer range for the high confidence environment, and shorter range for the low confidence environment.

Wind Uncertainty

The previous section was a good example of a WEZ analysis for a particular rifle. The intent was to study the hit percentage of that rifle in several different confidence environments comprised of entirely different wind, range, precision and velocity uncertainty sets. We're going to change gears a little bit for the next several sections and consider the uncertainty of each variable in isolation, to determine how that variable alone affects hit percentage. *Looking at each variable separately teaches us how to assess the uncertainties of any shot and determine how critical each variable is to hitting the target.* This section will focus on the *wind uncertainty* element of the environment.

Since wind is such an important element in all aspects of long range shooting, it's not surprising that the subject is given a lot of attention in training classes and by technology developers. *Quantifying the effects of training and wind measurement in terms of hit percentage is the subject of this section.*

Whereas previous WEZ analysis included wind uncertainty as only one element of a scenario comprised of rifle, shooter, and ammunition effects, this section will assume *high confidence* in all elements except wind. We'll focus on how hit percentage can be improved if wind uncertainty is reduced either through training shooters to estimate wind better, or by equipping shooters with devices that can measure the wind along the line of sight.

	High Confidence Environment
[redacted]	[redacted]
Range Estimation	+/- 1 yard
Rifle/Ammo Precision	0.5 MOA
Velocity Consistency	10 fps SD

Table 16.3. High Confidence environment with all variables except wind.

Table 16.3 shows the high confidence parameters that will be used for all of the analysis in this section. The focus is on improving hit percentage for good shooters who are well equipped, so the medium and low confidence environments of previous sections are not considered here.

A shooters ability to hit a target with the dispersion elements represented in Table 16.3 will depend primarily on how well wind effects can be managed. Obviously, the best case scenario is when wind uncertainty can be eliminated completely. Currently, in the real world, the only time this is even close to possible is when the wind simply isn't blowing. It's worth modeling this scenario just to see how the hit percentage looks for such a *no wind* scenario, so that we can see how much hit percentage is degraded for various amounts of non-zero wind uncertainty.

	Shooter Skill in Wind Reading		
Condition	**Novice**	**Average**	**Elite**
Easy	+/- 3 mph	+/- 2 mph	+/- 1 mph
Medium	+/- 4 mph	+/- 3 mph	+/- 2 mph
Difficult	+/- 5 mph	+/- 4 mph	+/- 3 mph

Table 16.4. Approximate guide to estimating crosswind uncertainty for various wind conditions and shooter skill levels.

Table 16.4 is a general matrix used to characterize wind uncertainty for various conditions and shooter skill. The amount of wind uncertainty will depend on the shooters ability to read or measure wind, as well as the difficulty of the wind condition. A novice shooter in easy conditions may only be able to determine wind within +/-3 mph, while an elite wind reader can get within +/-1 mph. In difficult wind conditions, the same elite wind reader might only get within +/-3 mph, but the novice shooter suffers +/-5 mph of uncertainty. Figures 16.19 and 16.20 show the impact that wind uncertainty has on hit percentage for two different rifle systems: the .308 Winchester shooting 175 grain bullets at 2600 fps, and the higher performance 300 Winchester Magnum shooting high BC 230 grain Berger Hybrid bullets at 2700 fps. The two systems are modeled to show how hit percentage is affected by wind uncertainty for *different levels of ballistic performance.*

Consider the .308 Winchester at 1000 yards in zero wind. The group as shown in Figure 16.18 does not exceed the extents of the target, so the hit percentage in this scenario is 100%. However, if there's just +/- 1 mph of wind uncertainty, the group widens, and hit percentage goes from 100% to 87%. At +/- 2 mph, the hit percentage falls to 55%. If you're dealing with +/- 5 mph of wind uncertainty, the hit percentage drops to a dismal 25% at this same range. It's very clear that reducing wind uncertainty plays a primary role in successful long range shooting, possibly more important than anything else.

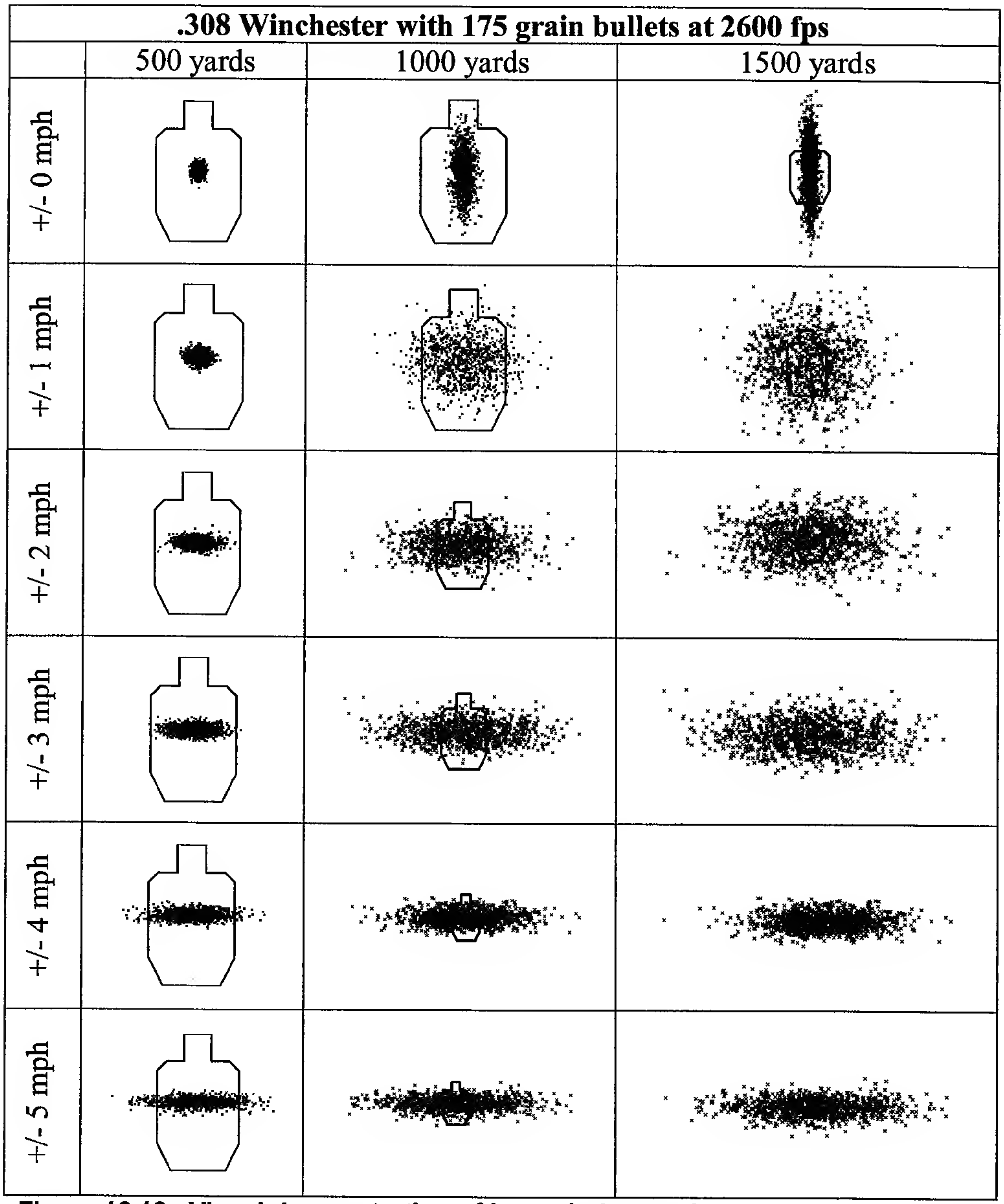
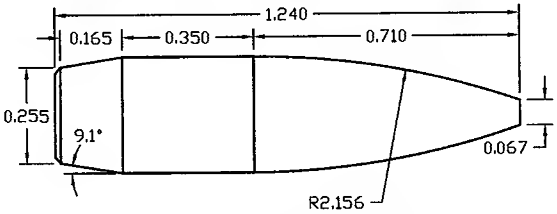


Figure 16.18. Visual demonstration of how wind spreads a group open. Notice that the vertical dispersion for each range is the same at each range, but the horizontal dispersion increases with wind uncertainty.

Unlike range, muzzle velocity, and atmospherics which can be measured and accounted for in a *deterministic* way, wind is very different. Wind is air in motion, and air is a highly dynamic fluid. The wind is not the same in speed and direction inch-to-inch as the bullet flies 100's of yards downrange. The bullets point of impact on the target is the cumulative effect of the entire wind field along its trajectory. As such, wind can be considered the biggest *non-deterministic* variable in long range shooting.

.308 Winchester

175 grain bullet at 2600 fps



Range Yards	**Wind Uncertainty**					
	0	**+/-1**	**+/-2**	**+/-3**	**+/-4**	**+/-5**
100	100%	100%	100%	100%	100%	100%
200	100%	100%	100%	100%	100%	100%
300	100%	100%	100%	100%	100%	100%
400	100%	100%	100%	100%	100%	99%
500	100%	100%	100%	100%	95%	89%
600	100%	100%	99%	94%	82%	70%
700	100%	100%	93%	80%	66%	56%
800	100%	99%	82%	66%	49%	44%
900	100%	96%	68%	54%	37%	33%
1000	100%	87%	55%	42%	28%	24%
1100	99%	75%	43%	33%	21%	19%
1200	95%	61%	34%	25%	16%	15%
1300	89%	48%	26%	19%	12%	12%
1400	82%	38%	20%	15%	10%	9%
1500	73%	30%	17%	11%	8%	7%

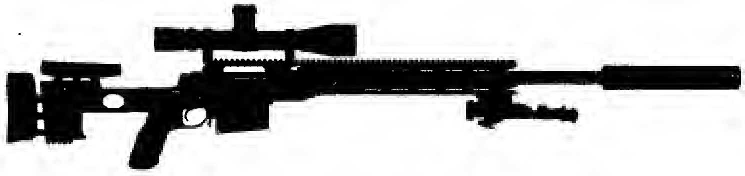
Figure 16.19. Wind uncertainty affects on hit percentage for .308.

Notice how dramatically hit percentage is affected for the .308 Winchester by the various degrees of wind uncertainty. Hit percentage at just 600 yards can be as low as 70% on the IPSC target in +/- 5 mph of wind uncertainty, and 99% in +/- 2 mph. Looking out to 1500 yards, hit percentage in zero wind can be as high as 73%[25], but reduced to 30% in just +/- 1 mph of uncertainty.

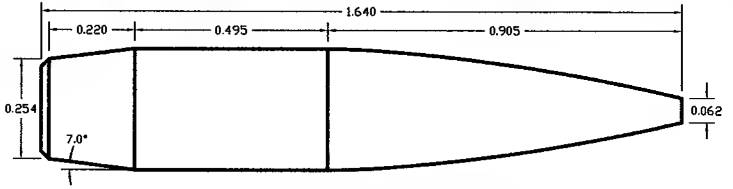
---

[25] Remember we're modeling a high confidence shooter and equipment, as well as a *perfect* ballistic solution, meaning centered groups. Such perfect trajectory prediction is unlikely at these extended ranges especially for the .308 Winchester, but is the only fair way to isolate and model how *wind* alone affects hit percentage.

300 Winchester Magnum



230 grain Berger Hybrid at 2700 fps



Range	Wind Uncertainty					
Yards	0	+/-1	+/-2	+/-3	+/-4	+/-5
100	100%	100%	100%	100%	100%	100%
200	100%	100%	100%	100%	100%	100%
300	100%	100%	100%	100%	100%	100%
400	100%	100%	100%	100%	100%	100%
500	100%	100%	100%	100%	100%	99%
600	100%	100%	100%	100%	98%	94%
700	100%	100%	100%	97%	91%	84%
800	100%	100%	99%	91%	79%	71%
900	100%	100%	94%	81%	67%	58%
1000	100%	100%	88%	69%	56%	45%
1100	100%	97%	79%	59%	45%	36%
1200	100%	92%	68%	49%	38%	30%
1300	99%	84%	57%	41%	31%	24%
1400	97%	74%	48%	33%	25%	18%
1500	91%	62%	39%	26%	20%	15%

Figure 16.20. Wind uncertainty affect on 300 Win Mag

The 300 Winchester Magnum can push a much higher BC 230 grain bullet a little faster than the .308 is able to push the 175 grain bullet. As a result, the hit percentage is maintained higher out to longer ranges. For example, in zero wind uncertainty, the 300 Win Mag retains 91% hit percentage out to 1500 yards, whereas the .308 Winchester is down to 73% in the same conditions, with the same dispersion sources. This happens because the higher ballistic performance round translates those same *sources* of dispersion into less *actual* dispersion. For example, the 10 fps standard deviation in muzzle velocity results in about 50" of vertical dispersion at 1500 yards for the .308 Winchester, whereas the same 10 fps standard deviation in MV results in more like 30" of vertical dispersion for the 300 Win Mag.

Furthermore, the .308 reaches transonic range around 800-900 yards, whereas the 300 Win Mag pushes supersonic range to 1300-1400 yards with the 230 grain Hybrids[26].

There is a dramatic improvement in hit percentage for the 300 Win Mag in all levels of wind uncertainty. For example at 1200 yards in +/- 2 mph wind uncertainty, the 300 Win Mag retains 68% hit percentage, where the .308 Winchester is down to 34% at the same range.

Interesting as it is to compare ballistic performance of different rounds, the focus of this chapter is to show the effect of reducing wind uncertainty through training or measurement. For example, if we have a good shooter who is a novice wind reader, we can improve his hit percentage from 45% to 69% with the 300 Win Mag at 1000 yards by teaching him to read wind within +/- 3 mph instead of +/- 5 mph in the same environment. This same increase in skill would elevate his hit percentage from 24% to 42% with the .308 Winchester at the same range. *There are few things that will improve hit percentage more than reducing wind uncertainty.*

Long range shooting instructors focus a great deal on wind reading for this very reason. Entire training courses are devoted to developing insight for reading wind in both civilian and military shooting disciplines. Those with a special *knack* for wind reading count themselves rare among their ranks, and often make successful coaches and/or instructors. Methods for teaching wind reading skills are as various as the applications for long range shooting. Known Distance (KD) competition ranges use flags of a standard size and color so shooters can judge wind by the same common indicator. Long range hunters and military snipers use a wider range of indicators including trees and grass to judge wind. Mirage is a valuable indicator for any shooting environment it can be seen in, so long as the shooter is skilled in *reading* the mirage. Given the vastness and in-exact nature of wind reading, it shouldn't be surprising that truly the best way to learn the skill is experience, and especially experience with a more skilled wind reader who can communicate their skills and knowledge to their students.

Figure 16.21. Kestrel hand-held weather meter.

Instrumentation can help a student of wind reading *hone* their abilities. The use of instrumentation can be as simple as carrying a handheld wind meter like a Kestrel anytime you're outdoors. Practice guessing at the wind speed that you feel and see in the indicators. Then measure and see how close you were. This exercise can substantially improve a novice's ability to determine wind speed in a short time.

The same idea can be applied on a greater scale by instrumenting entire ranges. A range with anemometers scattered about with their signals being networked and integrated into a full, average wind field for several targets can allow trainees to compare their wind estimates to the values measured by the sensor array. This sort of instrumented practice can really improve a shooters ability to accurately assess wind based on a range of natural indicators, and thus dramatically improve their hit percentage by minimizing wind uncertainty.

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[26] Even though this comparison is about wind performance, there are other elements that affect hit percentage as well, which are reflected in the results.

An instrumented range has great value for training, and developing a student shooters ability to read wind with greater confidence and more certainty. However those instruments are not practical for use in actual hunting and military applications. For these scenarios, a much smaller, portable, possibly even weapon mountable device is necessary which can look downrange and *profile* the effects of the wind optically. Such *wind profilers* are actually viable technology, and as of the printing of this book are being developed by government contractors for military use. It's difficult to tell how long it will take for these devices to mature to the point of being effective, and how long it might take before the technology is available to civilians. But when it is, there will be a quantum leap in the ability of long range shooters to engage targets thru difficult wind conditions.

The accuracy with which a futuristic wind profiler is able to resolve wind speed and direction at all points along a bullets trajectory is unknown. Some research indicates that +/- 1 mph may be possible. That level of certainty in all conditions is arguably impossible even for the most elite instinctive wind readers[27].

Consider the affect such an instrument would have on a shooters hit percentage. For the .308 Winchester, one could maintain 96% hit percentage out to 900 yards regardless of wind conditions. With a more normal limitation of +/- 4 mph, the hit percentage at that range would only be 37%. The 300 Winchester Magnum could see as much as 92% at 1200 yards, compared to 38% with +/- 4 mph of uncertainty at the same range.

Needless to say, the advent of field deployable wind profilers will provide one of the biggest improvements in hit percentage for long range shooting since laser rangefinders.

Before leaving this discussion of wind uncertainty, it's important to consider the effects of rifle cant (rolling the rifle to one side or the other). This subject was covered in more detail in a previous chapter, but it's worth mentioning here given its relevance to wind shooting. When considering *wind uncertainty* as we have in this chapter, the major focus has been on the wind speed. However, there are other uncertainties that can arise in the horizontal direction which result in challenges for judging the wind for long range shots. For example, if the rifles sight adjustments don't track vertically straight up a plumb line, the point of impact at long range will not be zeroed on the target, even in no wind conditions. Unfortunately this is a common pitfall that long range shooters can suffer from. It's very important to level your sights and verify vertically tracking sight adjustments so that your long range wind zero will be valid. Otherwise, your bullets will land somewhere that's not consistent with the wind speed and direction. This makes it very difficult, impossible even, to learn to read wind conditions.

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[27] Emphasis on *all conditions.* It's not uncommon for an elite wind reader to evaluate wind within +/- 1 mph in easy conditions with indicators, but to do the same in difficult conditions with little to no indicators, as in shooting across canyons, is highly unlikely.

Summary of wind analysis

- Wind is usually the greatest uncertainty in long range shooting, and the cause of most misses.
- Improving ballistic performance can increase hit percentage at long range, but even very high performance rounds are highly susceptible to wind uncertainty.
- Learning to accurately assess wind speed and direction can improve hit percentage dramatically. Therefore training and practice is perhaps the most worthwhile investment in hit percentage for windy environments.
- A shooters wind assessment skills take time and experience to develop. These skills can be sharpened by the use of wind measurement devices.
- Be sure to verify vertical tracking sights. This insures that your long range wind zero will truly be zero. Not verifying this can make it difficult or impossible to learn to read wind (since you can't have a long range wind zero if your sights don't track vertically).

Range Uncertainty

Accurately determining the range to a target is fundamentally important for successful long range shooting. Due to the bullets arcing trajectory, if the range is not known accurately, the shooter will over or under-shoot the intended point of impact.

There are many tools and methods used for measuring or estimating range including:

- Laser rangefinders
- Optical Rangefinders
- Use of maps/overhead imagery
- MIL reticle ranging
- Educated guessing

Figure 16.22. Vectronix PLRF-10 laser range finder.

Each of the above methods and tools have unique characteristics related to accuracy and reliability. Laser rangefinders are the most accurate (practical) way of measuring range, typically capable of getting within +/- 1 yard. But there are problems with laser rangefinders related to beam divergence and target reflectivity. Sometimes the intended target isn't reflective enough to register in its environment, so the shooter ends up ranging something else that's more reflective in the targets surroundings. Sometimes it could be a rock 5 yards in front of the target, or sometimes it could be a tree line 100 yards behind the target. Most tools and methods available for ranging targets become less accurate as the range increases. This is unfortunate since the most distant shots are the ones for which you need the most accurate range information.

This section is not intended to be a detailed study of the various tools and methods available for ranging targets. Rather, we will be assessing how hit percentage is affected by range uncertainty for a couple different rifle/ammo combinations. The .308 Winchester with 175 grain bullets at 2600 fps is chosen to represent the slower, heavier bullet performance class. The .243 Winchester with 105 grain bullets will represent the higher velocity class of rifle/ammo performance.

These two cartridge bullet classes are quite common for many applications ranging from varmint to medium game hunting, and tactical competitions.

Before breaking off into the individual assessments of each rifle, we'll first discuss the simulation parameters that will apply to both. Both rifles will be modeled in a *high confidence* environment as shown in Table 16.5, with the exception of range uncertainty which we'll consider at +/- 1 yard, +/- 10 yards, and +/- 50 yards.

	High Confidence Environment
Cross Wind Estimation	+/- 1 mph
Range Estimation	+/- 1 yard | +/- 10 yards | +/- 50 yards
Rifle/Ammo Precision	0.5 MOA
Velocity Consistency	10 fps SD

Table 16.5. High Confidence environment with all variables except range.

Uncertainties in wind, precision and velocity will be held constant at their *high confidence* levels in order to effectively isolate the effects of range uncertainty on hit percentage.

.308 Winchester

As previously stated, the .308 Winchester with 175 grain bullets is representative of a particular class of ballistic performance characterized by being relatively slow, thus producing a trajectory that's not very *flat*. It's still a very capable round at long range, but due to its performance, getting an accurate target range will be more critical to maintaining a high hit percentage compared to the faster .243 Winchester round.

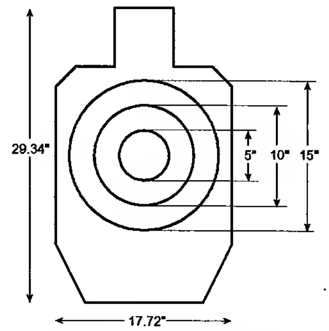


Figure 16.23. IPSC target dimensions with inscribed 5", 10" and 15" circles.

For this simulation exercise, the target array will be that shown in Figure 16.23. The multiple size rings (5", 10" and 15") are representative of various target classes including: varmints, medium and big game, as well as the IPSC silhouette which will be used to represent hit percentage for tactical shooting applications.

Figure 16.24 below shows examples of simulated groups at 800 yards for the three range uncertainty scenarios.

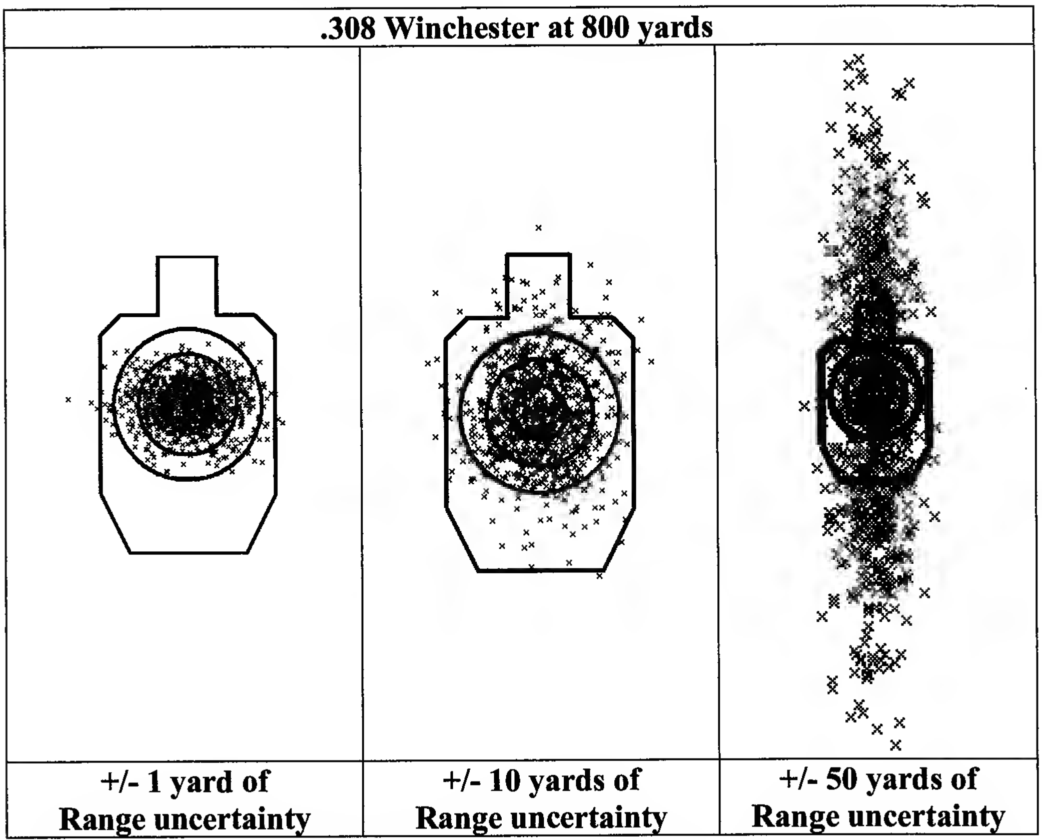


Figure 16.24. Effects of various levels of range uncertainty on vertical dispersion for .308 Winchester.

It's clear from Figure 16.24 that the shot group stretches out more vertically with increasing range uncertainty. At +/- 50 yards of uncertainty, the group is almost totally dominated by vertical dispersion. In this 800 yard scenario with the .308 Winchester, the hit percentage on the IPSC silhouette falls from 99% with +/-1 yard uncertainty, down to 98% for +/-10 yard uncertainty, but then plummets to 50% for the +/- 50 yard uncertainty scenario.

Hit percentages are affected at closer ranges for the smaller targets. Hit percentage is not affected much for the large targets until the range exceeds 600 yards or so. Of course this result is specific to the ballistic performance of the .308 Winchester, and the exact effect on hit percentage for a given range uncertainty will depend on how flat the trajectory is. Speaking of flatter trajectories, we'll now turn the analysis to the other cartridge; the .243 Winchester.

.243 Winchester

The .243 Winchester will represent the high end of ballistic performance in terms of a *flat shooting* round for this analysis. Of course there are other cartridges that are faster and flatter like the .220 Swift, .22-250, etc. However this analysis is being carried out to 1500 yards, which at those distances the tiny .22 caliber bullets have nearly no capability. The .243 Winchester is modeled with Berger 105 grain Hybrid bullets, which have quite a high BC (G7 BC of 0.278) and can be fired in excess of 3000 fps from 26" barrels. For this analysis, we'll model this bullet at 3000 fps MV.

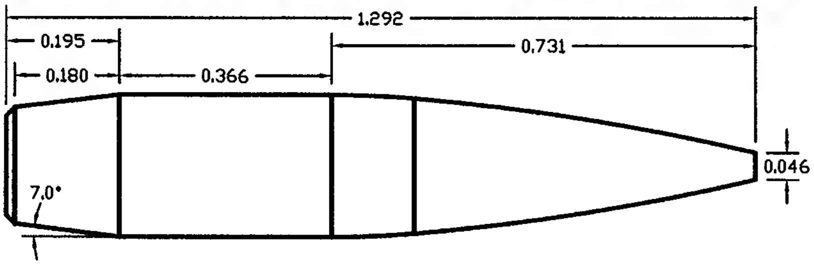
<table>
<tr><th colspan="2">.243 Winchester</th></tr>
<tr><td colspan="2"> </td></tr>
<tr><td colspan="2">
</td></tr>
<tr><td>Bullet</td><td>6mm 105 grain Berger Hybrid</td></tr>
<tr><td>G7 BC</td><td>0.278</td></tr>
<tr><td>Muzzle Velocity (26" barrel)</td><td>3000 fps</td></tr>
</table>

Figure 16.25. The .243 Winchester has a much higher MV than .308, so vertical dispersion is less for the same range uncertainty.

As expected, the flat trajectory of the .243 Winchester results in higher hit percentages with the same range uncertainty compared to the .308 Winchester. Figure 16.26 shows a graphical comparison of the group size at 800 yards. The vertical dispersion in the +/- 1 yard uncertainty target is not visibly different from the .308 Target shown previously in Figure 16.24. On the +/- 10 yard uncertainty target you can begin to see a minor difference. However on the +/- 50 yard uncertainty target, the difference in vertical dispersion between the .308 and .243 trajectories is obvious.

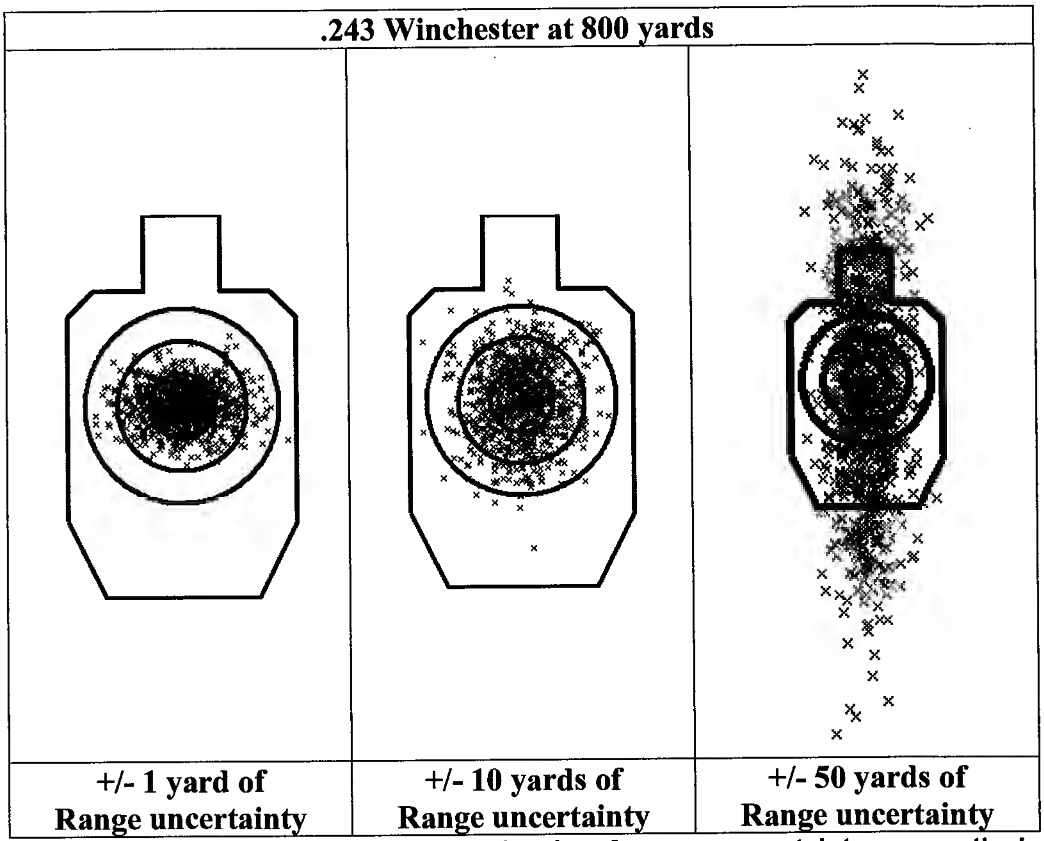


Figure 16.26. Effects of various levels of range uncertainty on vertical dispersion for .243 Winchester.

Of course the numerical results of the simulation also express a dramatic advantage in hit percentage for the flatter shooting .243 compared to the .308. The full data sets are given at the end of this section for all target sizes, but Table 16.6 contains a subset of the results for the 10" circle target and the IPSC silhouette.

Notice that for the +/- 1 yard, and +/- 10 yard uncertainty scenarios at 500 yards, hit percentage remains essentially 100% for both cartridges. This result is not surprising since 500 yards is not really that far, and the trajectory is not dropping off too sharply in either case. But for the +/- 50 yard range uncertainty scenario, both cartridges are missing the 10" circle quite a bit, and there are even misses on the IPSC silhouette at 500 yards for both cartridges.

Moving on to the 1000 yard comparisons, we can see that the .243 has a substantial advantage over the .308, even for the +/- 1 yard scenario. Remember that the +/- 1 yard of range uncertainty is very small, and can be considered to be zero range uncertainty for practical purposes. The fact that the .243 has a higher hit percentage in this case has more to do with its higher ballistic performance, i.e., being better in the wind (+/- 1 mph of wind uncertainty). Also, the higher average velocity of the .243 means it will exhibit less vertical dispersion from the same 10 fps SD in muzzle velocity variation than the .308.

Hit Percentages Comparisons for .308 and .243 for two different sized targets

	10" Circle		**IPSC Silhouette**	
Range	**.308**	**.243**	**.308**	**.243**
+/- 1 yard of range uncertainty				
500 yards	100%	100%	100%	100%
1000 yards	42%	71%	86%	98%
1500 yards	7%	14%	33%	53%
+/- 10 yards of range uncertainty				
500 yards	98%	100%	100%	100%
1000 yards	25%	51%	80%	97%
1500 yards	5%	10%	24%	41%
+/- 50 yards of range uncertainty				
500 yards	43%	61%	91%	99%
1000 yards	7%	14%	29%	52%
1500 yards	1%	2%	6%	12%

Table 16.6. The flatter shooting .243 retains a greater hit percentage at all ranges, on all targets compared to the .308.

Of course, as the range uncertainty grows, the advantage will further grow in favor of the .243. Its flat trajectory enables it to *absorb* more range error compared to a trajectory that has more drop.

Stepping out to 1500 yards you can see that the hit percentage for both cartridges is quite low. However, the .243 has exactly double the hit percentage as the .308 under the same conditions for the 10" target, and substantially higher hit percentage on the IPSC target at 1500 yards as well.

Practical application of the results

Of course it's nice to consider the effect of range uncertainty on hit percentage, and even compare different cartridges as an academic exercise, but there are some really interesting and actionable take-aways to consider.

For example, ranging targets using MIL dot reticles is a common practice for military snipers and also for hunters. The idea is to measure a target using a reticle graduated in MIL dots. A simple formula is applied which uses the actual target size in inches, and the size of the target in the scopes reticle to result in a range to the target. The method is sound, but is subject to

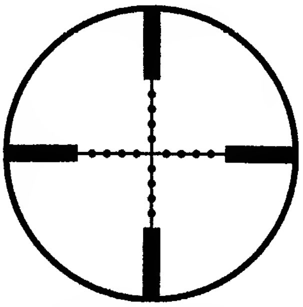


Figure 16.27. MIL dot reticle

uncertainties in all the variables. Thru practice and more sophisticated reticles, shooters can improve their accuracy with this ranging technique.

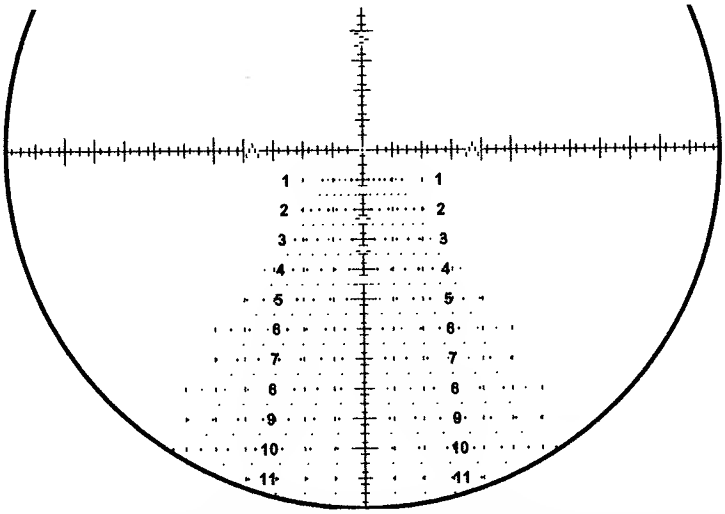


Figure 16.28. The TreMor 2 reticle is capable of MILing targets with 0.02 MIL resolution, which enables far more accurate range determination and directly improves hit percentage.

Consider a novice shooter with a basic MIL dot reticle, and little practice or experience. Given these tools and skills, a shooter may be able to estimate range to within +/- 50 yards at 1000 yards[28]. If the shooter is using a .308 Winchester in an otherwise high confidence scenario, our charts indicate that he only has a 29% chance of hitting an IPSC silhouette sized target from 1000 yards.

However, take this same shooter, train him on how to better estimate target sizes, give him a more sophisticated ranging reticle like the TreMor 2 shown in Figure 16.28 which allows for much finer measurement, and he may be able to reduce the uncertainty in his ranging down to +/- 10 yards for the same 1000 yard scenario. Doing so would more than double his chances of hitting the target, improving hit percentage from 29% to 80%!

The type of WEZ analysis demonstrated in this chapter is incredibly valuable not only to individuals striving to improve their skills and effectiveness at long range shooting. Consider the decision makers who control how military training budgets will be allocated. They're obviously interested in getting the most *bang for the buck* in terms of increases in hit percentage. Being able to calculate a meaningful hit percentage and demonstrate a significant improvement can assist those who decide on where to focus training resources, budgets, etc.

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[28] The accuracy of this technique is strongly dependent on distance. The farther the targets are away, typically the less resolution they can be ranged with.

The same type of analysis can be done to determine the importance of things related to laser rangefinder performance. If a narrower beam width means you're more likely to get a range on something within +/- 5 yards of your actual target as opposed to a wider beam that could be hitting things up to +/- 50 yards away, how does that impact your expected hit percentage? For the two cartridges specifically studied in this chapter, the WEZ results are presented for a high confidence environment and various degrees of range uncertainty. For other combinations of rifles, ammo, and environments, a specific WEZ analysis would have to be done. In other words, the trends demonstrated in this chapter are valid, but the specific numbers will change based on ballistic performance.

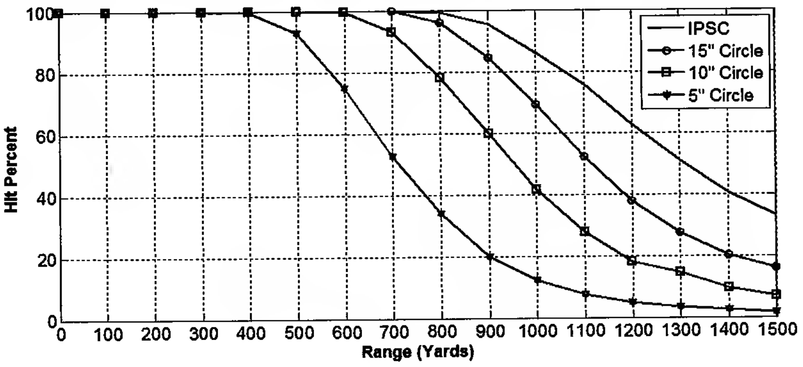
Summary of range uncertainty WEZ analysis

In general, we can say that:

- Range uncertainty has a major effect on hit percentage.
- In particular, hit percentage is affected on smaller targets at closer range, and larger targets at farther range.
- A flatter shooting cartridge/bullet combination will improve hit percentage given the same range uncertainty.
- Training to improve the accuracy of one's ranging abilities can result in direct and dramatic improvements in hit percentage.

.308 Winchester

Hit Percentage for +/- 1 yard of range uncertainty



Criteria

This WEZ was run for a high confidence set of environmental variables including the following:

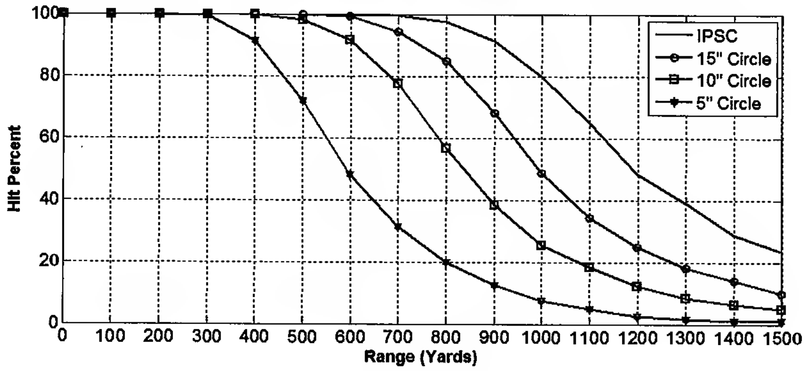
Wind determination: +/- 1.0 mph
Range determination: +/- 1 yards
Rifle/Ammo precision: 0.5 MOA
Velocity consistency: 10 fps SD

Range Yards	5" Circle	10" Circle	15" Circle	IPSC
100	100%	100%	100%	100%
200	100%	100%	100%	100%
300	100%	100%	100%	100%
400	100%	100%	100%	100%
500	93%	100%	100%	100%
600	75%	100%	100%	100%
700	53%	93%	100%	100%
800	34%	78%	96%	99%
900	20%	60%	85%	95%
1000	12%	42%	69%	86%
1100	7%	28%	52%	76%
1200	5%	18%	38%	63%
1300	4%	15%	28%	51%
1400	3%	10%	20%	41%
1500	2%	7%	16%	33%

Figure 16.29. 175 SMK (G7 BC = .243) at 2600 fps

.308 Winchester

Hit Percentage for +/- 10 yards of range uncertainty



Criteria

This WEZ was run for a high confidence set of environmental variables including the following:

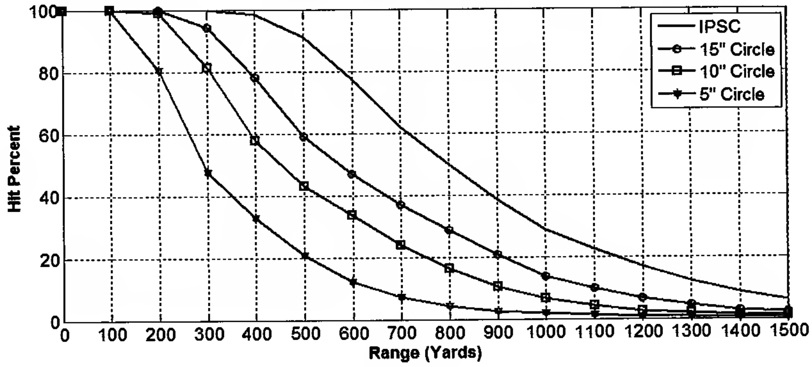
Wind determination: +/- 1.0 mph
Range determination: +/- 10 yards
Rifle/Ammo precision: 0.5 MOA
Velocity consistency: 10 fps SD

Range Yards	5" Circle	10" Circle	15" Circle	IPSC
100	100%	100%	100%	100%
200	100%	100%	100%	100%
300	100%	100%	100%	100%
400	91%	100%	100%	100%
500	72%	98%	100%	100%
600	48%	92%	99%	100%
700	31%	77%	94%	100%
800	20%	57%	85%	98%
900	12%	38%	68%	91%
1000	8%	25%	49%	80%
1100	5%	18%	34%	65%
1200	3%	12%	25%	48%
1300	2%	9%	18%	39%
1400	1%	6%	14%	29%
1500	1%	5%	10%	24%

Figure 16.30. 175 SMK (G7 BC = .243) at 2600 fps

.308 Winchester

Hit Percentage for +/- 50 yards of range uncertainty



Criteria

This WEZ was run for a high confidence set of environmental variables including the following:

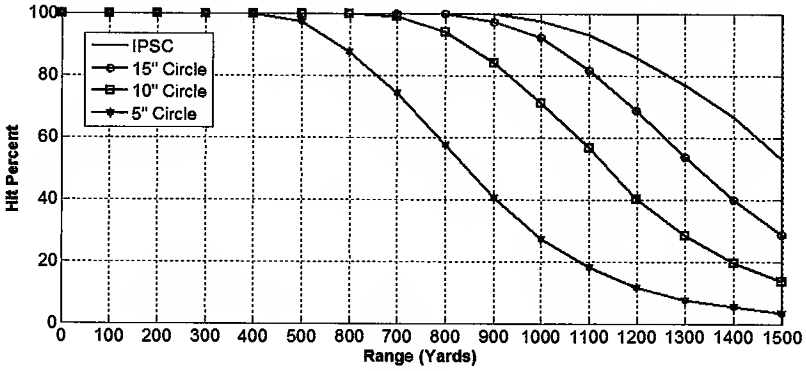
Wind determination: +/- 1.0 mph
Range determination: +/- 50 yards
Rifle/Ammo precision: 0.5 MOA
Velocity consistency: 10 fps SD

Range Yards	5" Circle	10" Circle	15" Circle	IPSC
100	100%	100%	100%	100%
200	81%	99%	100%	100%
300	48%	81%	94%	100%
400	33%	58%	78%	98%
500	21%	43%	59%	91%
600	12%	34%	47%	78%
700	7%	24%	37%	62%
800	4%	16%	29%	50%
900	3%	10%	21%	39%
1000	2%	7%	14%	29%
1100	1%	4%	10%	23%
1200	1%	3%	7%	17%
1300	1%	2%	5%	12%
1400	1%	1%	3%	9%
1500	1%	1%	2%	6%

Figure 16.31. 175 SMK (G7 BC = .243) at 2600 fps

.243 Winchester

Hit Percentage for +/- 1 yard of range uncertainty



Criteria

This WEZ was run for a high confidence set of environmental variables including the following:

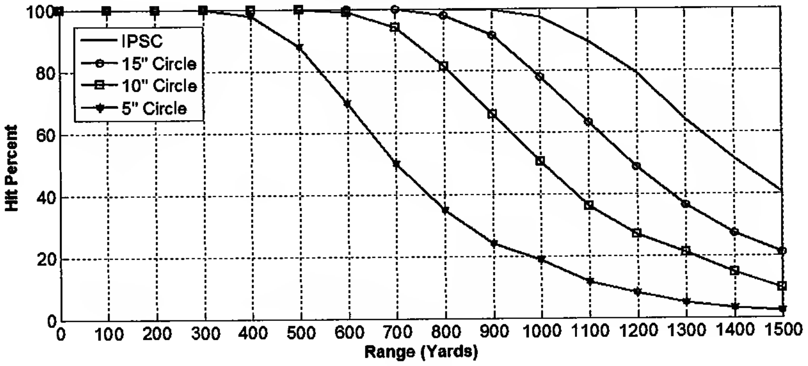
Wind determination: +/- 1.0 mph
Range determination: +/- 1 yards
Rifle/Ammo precision: 0.5 MOA
Velocity consistency: 10 fps SD

Range Yards	5" Circle	10" Circle	15" Circle	IPSC
100	100%	100%	100%	100%
200	100%	100%	100%	100%
300	100%	100%	100%	100%
400	100%	100%	100%	100%
500	97%	100%	100%	100%
600	87%	100%	100%	100%
700	74%	99%	100%	100%
800	58%	94%	100%	100%
900	40%	84%	97%	100%
1000	27%	71%	92%	98%
1100	18%	57%	82%	93%
1200	12%	40%	69%	86%
1300	8%	28%	54%	77%
1400	5%	20%	40%	67%
1500	3%	14%	29%	53%

Figure 16.32. Berger 105 grain Hybrid (G7 BC = .278) at 3000 fps.

.243 Winchester

Hit Percentage for +/- 10 yards of range uncertainty



Criteria

This WEZ was run for a high confidence set of environmental variables including the following:

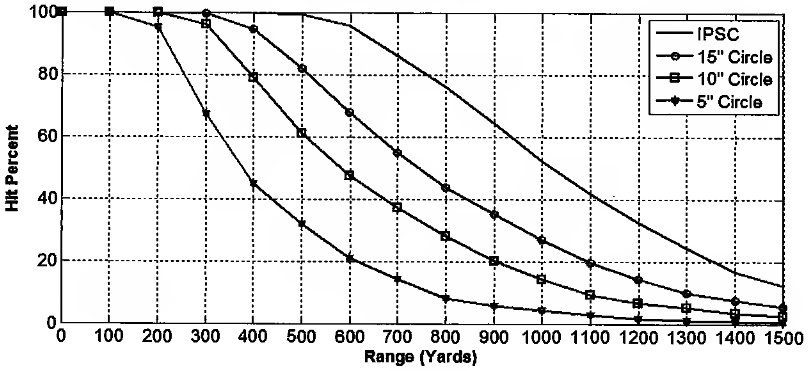
Wind determination: +/- 1.0 mph
Range determination: +/- 10 yards
Rifle/Ammo precision: 0.5 MOA
Velocity consistency: 10 fps SD

Range Yards	5" Circle	10" Circle	15" Circle	IPSC
100	100%	100%	100%	100%
200	100%	100%	100%	100%
300	100%	100%	100%	100%
400	98%	100%	100%	100%
500	88%	100%	100%	100%
600	70%	99%	100%	100%
700	50%	94%	100%	100%
800	35%	81%	98%	100%
900	24%	66%	91%	100%
1000	19%	51%	78%	97%
1100	12%	36%	63%	89%
1200	8%	27%	49%	79%
1300	5%	21%	36%	64%
1400	3%	15%	27%	51%
1500	2%	10%	21%	41%

Figure 16.33. Berger 105 grain Hybrid (G7 BC = .278) at 3000 fps.

.243 Winchester

Hit Percentage for +/- 50 yards of range uncertainty



Criteria

This WEZ was run for a high confidence set of environmental variables including the following:

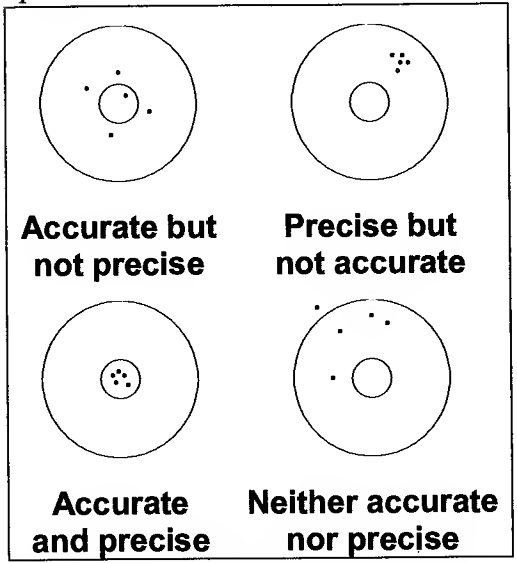
Wind determination: +/- 1.0 mph
Range determination: +/- 50 yards
Rifle/Ammo precision: 0.5 MOA
Velocity consistency: 10 fps SD

Range Yards	5" Circle	10" Circle	15" Circle	IPSC
100	100%	100%	100%	100%
200	95%	100%	100%	100%
300	67%	96%	100%	100%
400	45%	79%	95%	100%
500	32%	61%	82%	99%
600	21%	47%	68%	96%
700	14%	37%	55%	86%
800	8%	28%	44%	76%
900	6%	20%	35%	64%
1000	4%	14%	27%	52%
1100	3%	9%	20%	42%
1200	2%	7%	14%	33%
1300	1%	5%	10%	24%
1400	1%	4%	7%	17%
1500	0%	2%	6%	12%

Figure 16.34. Berger 105 grain Hybrid (G7 BC = .278) at 3000 fps.

Inherent Precision

In order to repeatably hit targets at long range, a rifle and shooter need to be capable of shooting *small groups* and centering them on the intended aim point.


Accurate but not precise **Precise but not accurate**

Accurate and precise **Neither accurate nor precise**

Figure 16.35. Examples of accuracy and precision.

Although small groups indicate a high degree of *precision*, it's commonly mistaken as *accuracy*. In fact, accuracy is entirely different. Accuracy is an indication of how a group of shots hits relative to the intended aim point, regardless of group size. Figure 16.35 demonstrates visually the difference between accuracy and precision. In words; precision is group size, and accuracy is centering the group.

Earlier sections of this chapter were dedicated to studying hit percentage scenarios in which groups are assumed to be centered (perfect accuracy) and misses are due to environmental influences and weapon/shooter performance (precision effects). To echo a statement made earlier; the point of isolating the variables is to learn their individual effects, so you can see how much each one affects hit percentage. This allows you to assess what the most limiting factors are for any given shot, and focus on getting them right, thus maximizing hit percentage.

For this example, we'll again consider a .308 Winchester with 175 grain bullets at 2600 fps.

This analysis will be done for only a *high confidence* environment in order to isolate the effect of precision alone. If we were to do the analysis in medium or low confidence environments, the effect of precision alone would be more difficult to determine.

	High Confidence Environment
Cross Wind Estimation	+/- 1 mph
Range Estimation	+/- 1 yard
[redacted]	[redacted]
Velocity Consistency	10 fps SD

Table 16.7. Environment set used to isolate effects of precision.

In this table, High, Medium and Low Precision correspond to 0.5 MOA, 1.0 MOA and 1.5 MOA groups respectively. These are the group sizes that the rifle/ammo/shooter combination is capable of at 100 yards.

The question we're studying in this chapter is: how much is hit percentage affected by *just* changes in rifle/ammo precision. In other words, if we have a rifle shooting 1 MOA groups at 100 yards, how much can long range hit percentage be improved if we work to get the rifle/ammo shooting 0.5 MOA groups at 100 yards? This is a very important and relevant question because of the effort and expense related to improving a rifles precision. It's quite easy to get commercial off the shelf rifles and ammo to produce 1.5 MOA precision, and that level of precision corresponds to a relatively low hit percentage, especially at long range on small targets. By applying a few known modifications to a rifle and ammo, it's not too difficult to achieve 1.0 MOA precision. However, in order to get a rifle shooting 0.5 MOA or better can take a great deal more effort and expense.

We'll run the simulation against an array of target sizes so the question can be answered for a number of applications. The target will be modeled as shown in Figure 16.36. It's the IPSC silhouette target with inscribed circles of 5", 10" and 15" in diameter. Hit percentages will be calculated for each of the circles and for the IPSC target itself.

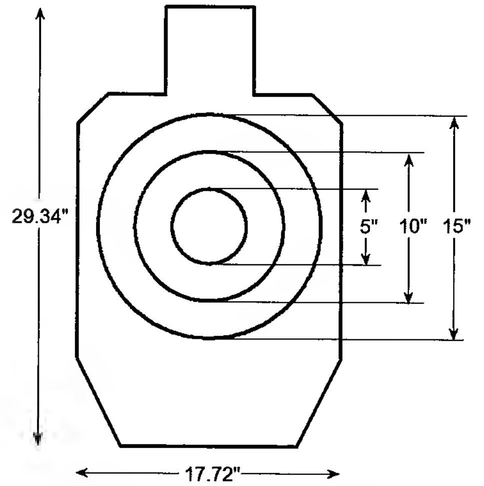
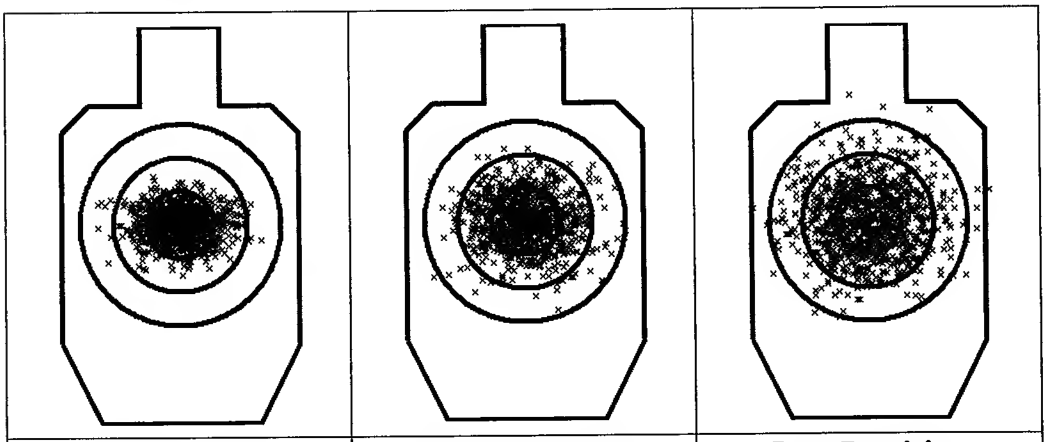


Figure 16.36. IPSC target dimensions with inscribed 5", 10" and 15" circles.

Note that for this analysis, bullet dispersion was modeled from the muzzle as a normal distribution, with a defined standard deviation. Specifically, the vertical and horizontal components of dispersion were given standard deviations that would result in 95% of shots hitting within the prescribed group sizes. For example, for the 1.0 MOA precision scenario, the standard deviation of dispersion is modeled as 0.25 MOA. We know from basic statistics that +/- 2σ (two standard deviations) results in 95% confidence intervals. In other words, +/- two times the standard deviation of 0.25 MOA means that 95% of the samples from the population will be within +/- 0.5 MOA of the center, or 1.0 MOA total group size. Horizontal and vertical dispersion are modeled with the same standard deviation to produce a round group in which 95% of shots fall within a 0.5 MOA radius to produce a "1.0 MOA" group. Note that for this model, 5% of shots will fall outside the nominal group size, which is a known effect of the statistical model. Of course there are other statistical means by which to model shot dispersion, but the above is the method used for this analysis.

Now that we have a clear understanding of how shot dispersion is modeled, take a look at the three shot patterns in Figure 16.37. Figure 16.37 shows the simulated shot patterns for the 3 precision scenarios at 600 yards. You can see the higher precision targets have tighter groups. For the highest precision (0.5 MOA) group, we would expect 95% of the shots to be inside a 3.1" group (0.5 MOA at 600 yards). However, you can see that the shot group far exceeds this size (the smallest circle is 5"). The reason for the shot group being substantially larger than 3.1" at 600 yards is due to the other uncertainties of the environment that are being modeled, and increase dispersion beyond 100 yards. Those environmental conditions are what we've called *High Confidence* in previous modeling scenarios, and include:

- Range within +/- 1 yard. This uncertainty has very little effect on shot dispersion.
- Muzzle velocity standard deviation of 10 fps.
- Wind uncertainty of +/- 1 mph. This uncertainty is responsible for widening the group beyond the inherent dispersion of the rifle/ammo/shooter.



High Precision **0.5 MOA**

Medium Precision **1.0 MOA**

Low Precision **1.5 MOA**

Figure 16.37. Various (short range) precision levels projected out to long range on the IPSC silhouette, with environmental uncertainties modeled.

Now that the model has been fully explained, we'll move on to addressing the results. Refer to Figure 16.37, and note that from the highest to the lowest precision scenario, *most* of the shots fall on the IPSC silhouette at 600 yards. Even though the shot group is tighter and more centrally located on the higher precision targets, a hit is a hit, and so when considering the large IPSC target at 600 yards, the model indicates 100% hit probability for all 3 precision levels (small number of misses still result in total hit probability rounding to 100%). This result is specific to this range and target size, but it indicates a trend that will become clear shortly.

Next consider the 15" (largest) circle within the IPSC silhouette. Note that in the high precision scenario, almost all of the shots hit inside this circle, whereas in the low precision scenario there are a number of misses. In fact the hit percentage is 100% vs. 98% for the 15" circle at 600 yards. A small difference, but a difference none-the-less. Remember that there was effectively no difference in hit percentage for the full IPSC silhouette.

Now move down to the 10" circle. It's clear that there are far more misses on this target size for the low precision scenario compared to the high precision one. In fact, the model predicts a 99% hit percentage for the high precision, 10" target which is substantially greater than the 84% prediction for the low precision 10" target at 600 yards.

Finally, consider the 5" circle which falls from 73% for the high precision scenario to 34% for low precision; a difference of more than 2 times hit percentage.

From the preceding several paragraphs, we can conclude that at 600 yards, *hit percentage is affected by precision more for smaller targets than it is for larger targets.*

The figures and data at the end of this chapter tabulate the full results of the simulation from zero to 1500 yards. Note that the trends we observed for 600 yards are more or less true at all ranges.

Take Figure 16.38 for example, which contains the hit percentage results for the 5" circle target. At just 400 yards, the precision difference from high to low results in hit percentage dropping from 99% to 69%. But consider the 10" target at the same range (400 yards). For the 10" target, the hit percentage only drops from 100% to 99%.

The trend continues for larger targets. The larger the target is, the less affect precision has on hit percentage. This result makes sense when you think about it. ***At long range, the environmental uncertainties play a much greater role in dispersion. But at short range, the environmental uncertainties are less important and so hit percentage is more driven by raw precision capability.***

Consider these results from a *return on investment* point of view, where the investment is related to time and money spent to improve precision. Suppose it costs $500 and 5 hours to improve the raw precision capability of a particular rifle from 1.5 MOA to 1.0 MOA (at 100 yards). In order to improve the precision even farther, from 1.0 MOA to 0.5 MOA, it will cost substantially more time and money, probably more than twice as much; call it $1,500 and 15 hours to go from 1.0 MOA to 0.5 MOA. The numbers aren't really important, except to recognize that it takes a whole lot of money and effort to make small improvements in precision once precision reaches a certain level. How much improvement in hit percentage can you really expect for all that effort? Well, it depends.

First we'll consider precision from a varmint hunters perspective. Varmint shooting is characterized by small targets, so we'll use the 5" circle results from the statistical model. At 600 yards, your hit percentage can be improved from 34% to 53%, which is a 19% improvement if you improve precision from 1.5 MOA to 1.0 MOA. If you continue working to improve precision down to 0.5 MOA, your hit percentage is further improved to 73%, which is another 20% improvement. What this is showing us is that although the effort required to improve precision becomes exponential as precision increases, the increase in hit percentage is relatively linear. The plots in Figures 16.38, 16.39 and 16.40 show this graphically. If you were to continue to work and improve precision to the 0.25 MOA level which would take substantially more work and money than it took to get to 0.5 MOA, you would likely only see an additional 10% improvement in hit percentage at 600 yards on the 5" circle (extrapolating from the previous results). Again, hit percentage is affected less or not at all for larger targets.

Even though precision enhancements become more difficult to achieve once precision is high, in this application involving small targets, you actually do get a significant increase in hit percentage by continuous improvements in precision.

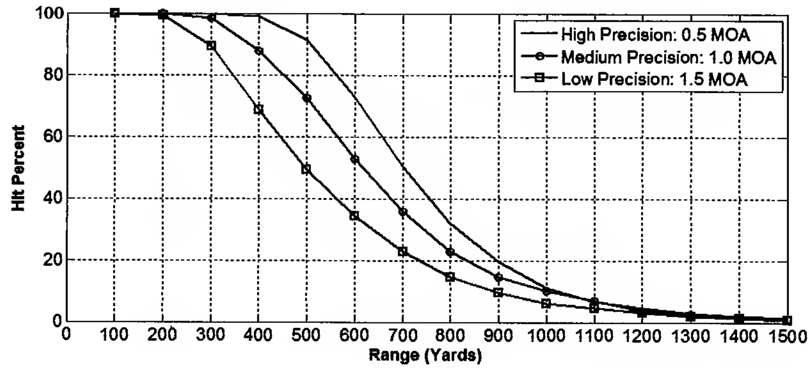
Now consider another shooting application; tactical shooting using IPSC silhouette targets. Consider that target at 1000 yards. The model predicts that a precision increase from 1.5 MOA to 1.0 MOA improves hit percentage from 77% to 82%; an increase of only 5%. Likewise, if precision is further enhanced from 1.0 MOA to 0.5 MOA, hit percentage only improves by an additional 4% at the same range. Extrapolating these results, we might only expect hit percentage to be improved by an additional 2% or 3% if we improved the precision of the rifle to 0.25 MOA. Clearly *in this application* (involving the large target at long range), the benefits of high precision are not as great.

Summary of inherent precision effect on hit percentage

The effect of rifle precision on hit percentage can be summarized by the following statements which are supported by the analysis.

- When considering small targets at relatively short range (under 500 yards), significant improvements in hit percentage can be realized by improving rifle precision from 1.5 MOA to 1.0 MOA, and even further to 0.5 MOA.
- At longer ranges on larger targets, hit percentage is still improved thru improving short range precision, however the improvement is less compared to what it is for shorter ranges and smaller targets.

Hit Percentage for 5" circle target



Criteria

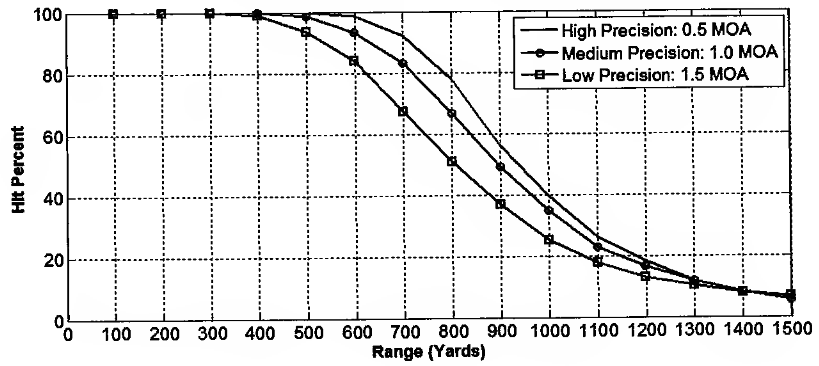
This WEZ was run for a high confidence set of environmental variables including the following:

Wind determination: +/- 1.0 mph
Range determination: +/- 1 yard
Rifle/Ammo precision: 0.5, 1.0, and 1.5 MOA
Velocity consistency: 10 fps SD

Range Yards	High Precision 0.5 MOA	Medium Precision 1.0 MOA	Low Precision 1.5 MOA
100	100%	100%	100%
200	100%	100%	99%
300	100%	98%	89%
400	99%	88%	69%
500	91%	73%	49%
600	73%	53%	34%
700	50%	36%	23%
800	32%	23%	15%
900	20%	15%	10%
1000	11%	10%	6%
1100	7%	7%	5%
1200	5%	4%	3%
1300	3%	3%	2%
1400	2%	2%	1%
1500	1%	1%	1%

Figure 16.38. .30 cal 175 grain SMK (G7 BC = .243) at 2600 fps.

Hit Percentage for 10" circle target



Criteria

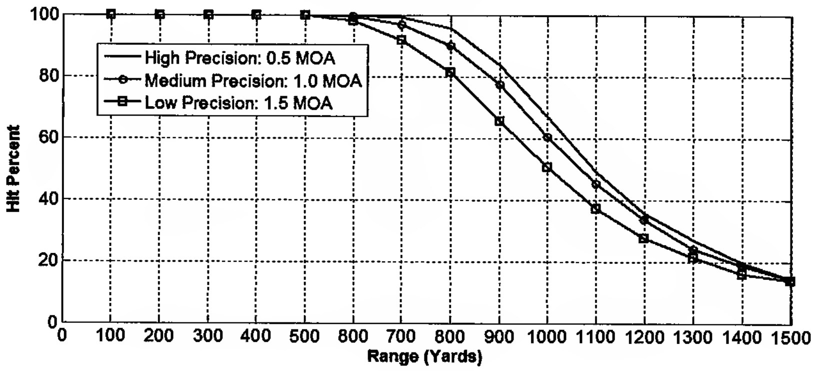
This WEZ was run for a high confidence set of environmental variables including the following:

Wind determination: +/- 1.0 mph
Range determination: +/- 1 yard
Rifle/Ammo precision: 0.5, 1.0, and 1.5 MOA
Velocity consistency: 10 fps SD

Range Yards	High Precision 0.5 MOA	Medium Precision 1.0 MOA	Low Precision 1.5 MOA
100	100%	100%	100%
200	100%	100%	100%
300	100%	100%	100%
400	100%	100%	99%
500	100%	99%	94%
600	99%	93%	84%
700	92%	83%	67%
800	78%	67%	51%
900	56%	49%	37%
1000	40%	35%	25%
1100	26%	23%	18%
1200	18%	17%	13%
1300	12%	12%	10%
1400	8%	8%	8%
1500	6%	6%	7%

Figure 16.39. .30 cal 175 grain SMK (G7 BC = .243) at 2600 fps.

Hit Percentage for 15" circle target



Criteria

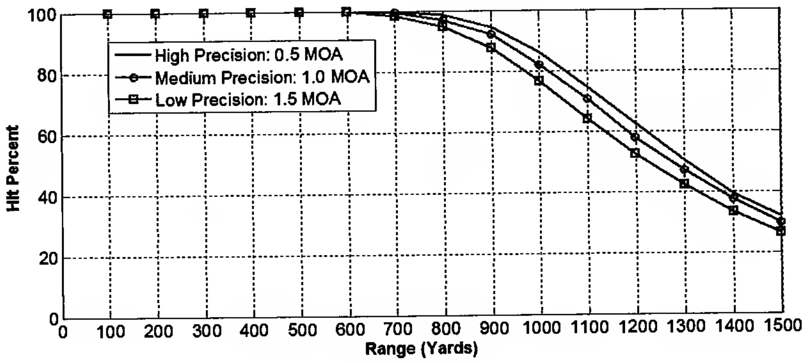
This WEZ was run for a high confidence set of environmental variables including the following:

Wind determination: +/- 1.0 mph
Range determination: +/- 1 yard
Rifle/Ammo precision: 0.5, 1.0, and 1.5 MOA
Velocity consistency: 10 fps SD

Range Yards	High Precision 0.5 MOA	Medium Precision 1.0 MOA	Low Precision 1.5 MOA
100	100%	100%	100%
200	100%	100%	100%
300	100%	100%	100%
400	100%	100%	100%
500	100%	100%	100%
600	100%	100%	98%
700	99%	97%	92%
800	96%	90%	81%
900	84%	77%	66%
1000	67%	61%	51%
1100	49%	45%	37%
1200	36%	34%	28%
1300	27%	24%	21%
1400	20%	19%	16%
1500	15%	14%	14%

Figure 16.40. .30 cal 175 grain SMK (G7 BC = .243) at 2600 fps.

Hit Percentage for IPSC sillouhette target



Criteria

This WEZ was run for a high confidence set of environmental variables including the following:

Wind determination: +/- 1.0 mph
Range determination: +/- 1 yard
Rifle/Ammo precision: 0.5, 1.0, and 1.5 MOA
Velocity consistency: 10 fps SD

Range Yards	High Precision 0.5 MOA	Medium Precision 1.0 MOA	Low Precision 1.5 MOA
100	100%	100%	100%
200	100%	100%	100%
300	100%	100%	100%
400	100%	100%	100%
500	100%	100%	100%
600	100%	100%	100%
700	100%	100%	99%
800	99%	97%	95%
900	94%	92%	88%
1000	86%	82%	77%
1100	75%	71%	64%
1200	63%	58%	52%
1300	50%	47%	42%
1400	39%	38%	33%
1500	32%	30%	26%

Figure 16.41. .30 cal 175 grain SMK (G7 BC = .243) at 2600 fps.

Muzzle Velocity Effects

The preceding sections have considered hit percentage for a combination of variables including; wind uncertainty, range uncertainty and inherent rifle/shooter precision. This section will consider the effects of muzzle velocity consistency, in terms of standard deviation. But first, we will look at how *average* muzzle velocity affects hit percentage thru increased ballistic performance.

Average Muzzle Velocity

Muzzle velocity is one of the most common metrics thought to affect ballistic performance, or at least performance potential. Higher average muzzle velocity increases hit percentage by providing greater resistance to wind deflection, and by reducing vertical dispersion for a given variation in muzzle velocity.

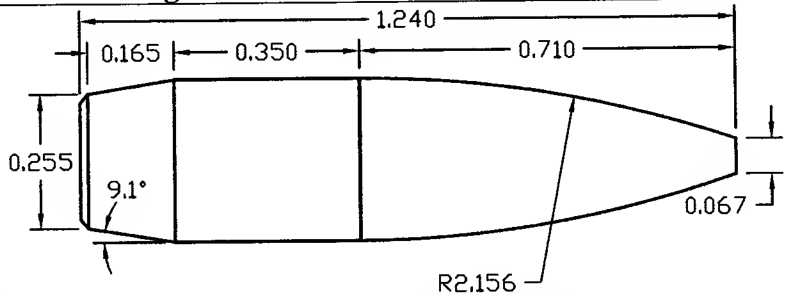
There are several practical ways in which shooters can affect muzzle velocity for a given bullet. The choice that affects muzzle velocity the most is the choice of cartridge. For example, a .30 caliber 175 grain bullet can have a muzzle velocity as low as 2500 fps from a short barreled .308 Winchester, or over 3300 fps from a large magnum. The choice of cartridge has the greatest affect, but in terms of equipment, it's the most difficult arrangement to make, since larger cartridges require larger bolt faces, which is not always possible without going to a whole new action.

Another way to affect muzzle velocity of a given bullet weight is thru barrel length. This variable can be affected more easily than cartridge choice in most cases because it's just a matter of re-barreling an existing rifle chambered for the same round. Thru barrel length alone, the velocity of a 175 grain bullet fired from a .308 Winchester can span from about 2500 fps in a 16" barrel to over 2800 fps in a 30" barrel with the same load. The 300 fps span in velocity is not as great as the increase possible by using a larger cartridge, but is still quite significant.

A relatively small effect in muzzle velocity for a given bullet/cartridge/barrel length is the pressure to which the ammunition is loaded. Ammunition loaded to the design operating pressure for a given cartridge compared to ammo loaded right at or over maximum typically nets less than 100 fps gain in velocity. Many hand loaders focus on how to get more velocity from a given rifle by loading the ammo to high pressures. These efforts rarely produce significant velocity gains without causing problems. As the following analysis will show, small increases in muzzle velocity don't have a great impact on hit percentage anyway.

To illustrate how much of an effect average velocity has on hit percentage, we'll consider the following analysis which involves a .30 caliber 175 grain bullet between 2500 fps and 3300 fps. The analysis will take place with the *high confidence* environmental variables which is 0.5 MOA rifle/shooter groups, +/- 1 mph wind uncertainty, +/- 1 yard of range error, and 10 fps standard deviation in muzzle velocity. Hit percentage will be modeled against the IPSC silhouette target. Later in this section we'll focus on how the standard deviation in muzzle velocity affects hit percentage.

175 grain bullet from 2500 fps to 3400 fps



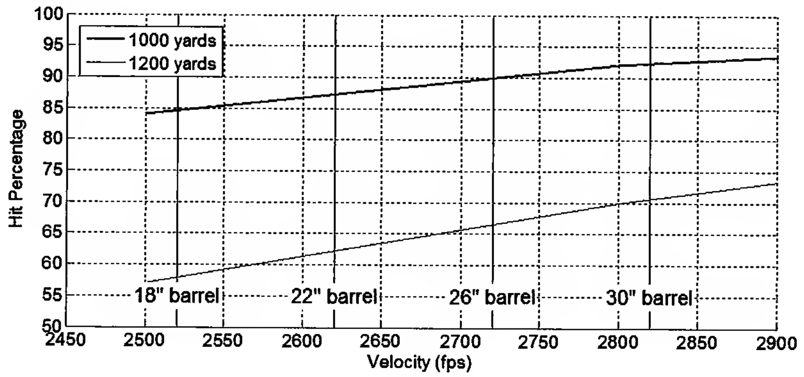
Range Yards	Muzzle Velocity			
	2500	2800	3100	3400
100	100%	100%	100%	100%
200	100%	100%	100%	100%
300	100%	100%	100%	100%
400	100%	100%	100%	100%
500	100%	100%	100%	100%
600	100%	100%	100%	100%
700	100%	100%	100%	100%
800	99%	99%	100%	100%
900	93%	97%	99%	100%
1000	84%	92%	96%	98%
1100	69%	81%	88%	93%
1200	57%	70%	80%	85%
1300	47%	57%	70%	77%
1400	36%	48%	59%	65%
1500	28%	39%	50%	53%

Figure 16.42. Muzzle velocity effects on hit percentage in a high confidence environment on the IPSC target.

Figure 16.42 shows the hit percentage on the IPSC silhouette as a function of range and muzzle velocity. It's clear that a *big* increase in muzzle velocity has a significant effect on hit percentage. For example from 2500 fps to 3400 fps, the hit percentage is increased from 84% to 98% at 1000 yards, and from 28% to 53% at 1500 yards. This can be considered a maximum effect on hit percentage for this bullet over the range of practical muzzle velocities, achievable only by going from a small to very large capacity cartridge.

The effect of barrel length can realistically be represented by a 300 fps difference in muzzle velocity which is represented by each column in Figure 16.42. Notice that by increasing MV from 2500 fps to 2800 fps, the hit percentage is increased from 84% to 92% at 1000 yards. This is roughly the affect of going from a 16" barrel to a 30" barreled .308 Winchester. Figure 16.43 considers the matter of barrel length in more detail.

Effect of Barrel Length and MV on Hit Percentage for .308 Win



	Muzzle Velocity (fps)	Hit Percentage	
		1000 yards	1200 yards
18" barrel	2520 fps	85%	58%
22" barrel	2620 fps	87%	62%
26" barrel	2720 fps	90%	67%
30" barrel	2820 fps	92%	71%

Figure 16.43. Barrel length effects on MV and hit percentage.

In Figure 16.43 we see the muzzle velocity and hit percentage for .308 Winchester barrel lengths from 18" to 30" in 4" increments. Going from 18" to 22" only increases hit percentage by 2%; from 85% to 87% at 1000 yards, and from 58% to 62% at 1200 yards. Basically, for every 4" of barrel length between 18" and 30", this particular combination produces 100 fps more velocity which translates to about 2% increase in hit percentage at 1000 yards, and 4% increase in hit percentage at 1200 yards.

Of course these results are specific to this bullet and cartridge, but are representative for this common class of weapon.

The results of this average muzzle velocity analysis are clear. ***It is possible to increase hit percentage a noticeable amount by increasing barrel length and MV, but only if great increases are made. Increasing barrel length in 4" increments only affects hit percentage by a small amount (2%) at 1000 yards, and slightly more (4%) at 1200 yards.***

This conclusion is valid for the specific analysis done on the full IPSC silhouette target. If the same analysis were done on a smaller target, hit percentage would probably have been affected more by average MV.

Consistency of Muzzle Velocity: Effect on Hit Percentage

As stated previously, muzzle velocity affects hit percentage in two ways; one is the average muzzle velocity which affects ballistic performance (which was just covered in the preceding section). The other is *consistency* of muzzle velocity, which affects vertical shot dispersion (faster shots hit higher, while slower shots hit lower). The remainder of this chapter will focus on the effects of muzzle velocity consistency on hit percentage.

The analysis will proceed similar to how it was done for: cross wind uncertainty, range uncertainty, and precision. Other than velocity consistency, all other elements of the environment will be modeled as *high confidence*. Table 16.8 below shows the simulation matrix for the following analysis.

	High Confidence Environment		
Cross Wind Estimation	+/- 1 mph		
Range Estimation	+/- 1 yard		
Rifle/Ammo Precision	0.5 MOA		
Velocity Consistency	10 fps SD	15 fps SD	20 fps SD

Table 16.8. Environment set used to isolate effects of MV SD.

The actual muzzle velocity that's modeled for each shot in the simulation is determined by the normal distribution as follows. 67% of the shots are modeled to be within +/- 1σ (one standard deviation) from the average, 95% of the shots are within +/- 2σ (two standard deviations) and 99% of the shots are within +/- 3σ (three standard deviations) of the average. In other words, if the average muzzle velocity is 2600 fps, and the standard deviation is 10 fps, then;

- 67% of the 1000 simulated shots will be between 2590 fps and 2610 fps.
- 95% of the shots will be between 2580 and 2620 fps.
- 99% will be between 2570 and 2630 fps.

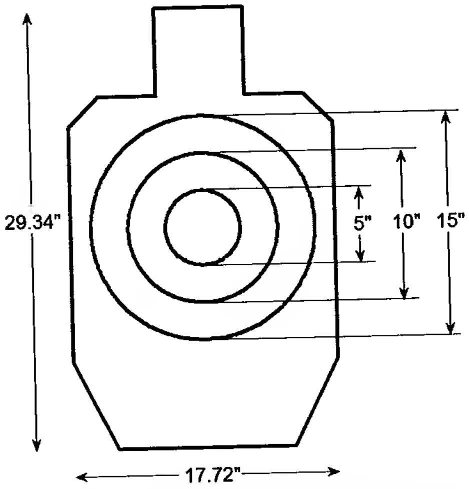


Figure 16.44. IPSC target dimensions with inscribed 5", 10" and 15" circles.

The analysis will be completed using the same model for .308 Winchester with 175 grain bullets at 2600 fps average velocity in standard sea level conditions.

The full results of this analysis are provided at the end of the chapter for the target array shown in Figure 16.44. Let's discuss some of the more interesting results here.

First thing that's apparent from the results is that hit percentage is improved as the muzzle velocity standard deviation is reduced. That's a good *reality check* that the model is working properly.

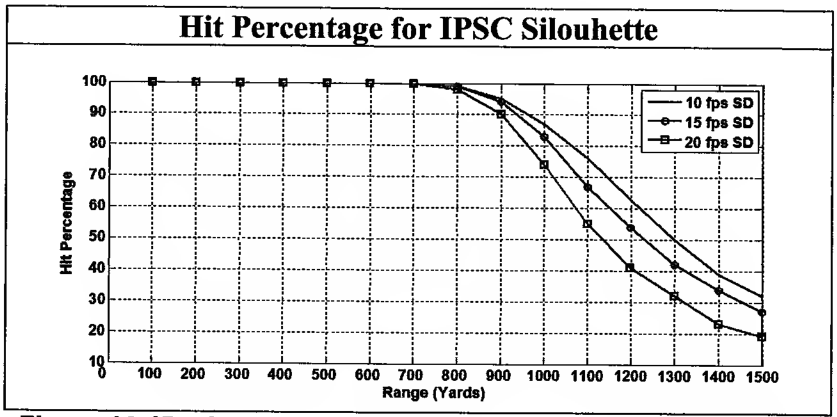


Figure 16.45. .30 cal 175 grain SMK (G7 BC = .243) at 2600 fps.

Figure 16.45 above shows how much hit percentage is affected by MV standard deviation for the IPSC silhouette target. According to these results, hit percentage is improved more when the MV SD is reduced from 20 fps to 15 fps than from 15 fps to 10 fps. For example, at 1000 yards, the hit percentage is improved by 9% (from 74% to 83%) by reducing SD from 20 fps to 15 fps. But if SD is further reduced from 15 fps to 10 fps, the hit percentage only improves another 4% from 83% to 87%. Given the unique shape of the IPSC target (tall and narrow), we should consider another target size to see if we get the same result.

Consider the 10" circle target which is more representative of the vital area for medium to large game animals.

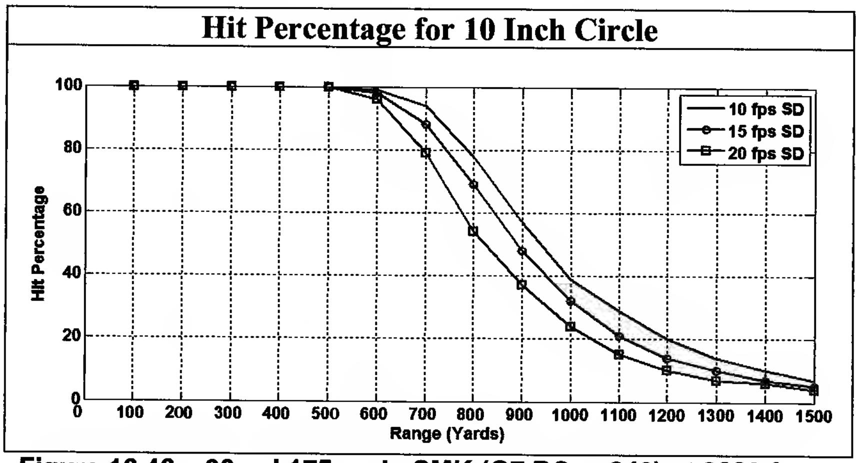


Figure 16.46. .30 cal 175 grain SMK (G7 BC = .243) at 2600 fps.

For the 10 inch circle target, we can see that the improvement in hit percentage is more linear as SD is reduced. At 1000 yards, hit percentage is improved from 24% to 32% (8% improvement) by reducing SD from 20 fps to 15 fps. Then as SD is further reduced from 15 fps to 10 fps, hit percentage improves another 7% from 32% to 39%.

Regarding available ammunition types, a Standard Deviation (SD) of 20 fps is considered relatively poor consistency, and is generally representative of mass produced factory ammo. 15 fps is considered better than average for factory produced ammunition, but still substandard for those who hand-load their own ammunition. 10 fps or less SD is typically the goal of most hand-loaders, and very few commercially available ammo suppliers are capable of producing ammo with SD's under 10 fps[29].

Of course the specific, numeric results of this analysis only apply directly to the rifle and ammo combination that was modeled: the .308 Winchester with 175 grain bullets at 2600 fps. Although the specific results would be different for different rifles/ammo types, we can expect the same trends in the results, and the same order of magnitude improvements in hit percentage as it relates to standard deviation of muzzle velocity.

One shooting discipline that the current analysis is highly relevant to is long range NRA *bull's-eye* style target shooting. The long range target has a 10" diameter X-ring for conventional sling shooters. For F-class shooters, the 10 ring is 10" in diameter and the X-ring is 5". These targets are used for all shooting at 800, 900 and 1000 yards for both unrestricted and Palma/F-TR rifles. Looking at Figure 16.46, we can get an idea of how many X's (or 10's for F-class) would be likely based on the *high confidence* uncertainty environment combined with various levels of ammunition consistency.

For example at 1000 yards with this rifle/ammo combination, +/- 1 mph wind uncertainty, and a 0.5 MOA precision capable rifle, we would expect to shoot about 39% X's (or 10's on the F-class target) if our SD was 10 fps. But we would only expect 24% X's (or 10's on the F-class target) if the SD was 20 fps.

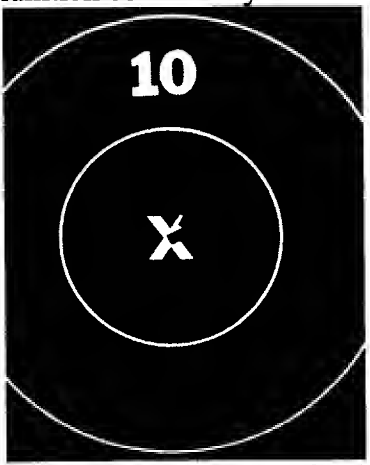


Figure 16.47. Target fired by the author in the 800 yard stage of a Palma course.

The target shown to the right was fired by the author in the 800 yard stage of a Palma course. In this case, the 'X-count' was 16 out of 17 shots which included 2 *sighters* (94% hit percentage on the 10" circle). According to Figure 16.46, the hit percentage for the 10" circle at 800 yards is only 79%, even for the lowest MV SD of 10 fps. But remember, that's based on a 175 grain bullet at 2600 fps. The target in Figure 16.47 was fired with 185 grain Berger LRBT *Juggernaut* bullets, at a muzzle velocity of 2800+ fps. It was a rare *no wind* morning, and the rifle/shooter capable of 0.5 MOA precision or better. Just for kicks, I plugged the above parameters into the simulation to see what it would calculate for group size and hit

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[29] Applied Ballistics Munitions (ABM) produces high quality ammunition with Standard Deviations of 10 fps or less.

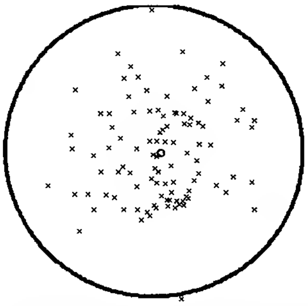


Figure 16.48. 10 inch *X-ring* target simulated with same conditions as the real target in Figure 16.47.

percentage. The result for a 100 shot simulation is shown in Figure 16.48. As you can see, when run with the same parameters as the actual target was fired, the simulation predicts a very close representation of reality. A hit percentage of 99% on the 10" X-ring was calculated for this scenario.

This brings up an interesting question regarding the difference in performance between a 175 grain bullet at 2600 fps vs. a 185 grain bullet at 2800+ fps. *How would the hit percentage change in relation to SD for other classes of ballistic performance?* To address this question, the 175 grain bullet was modeled at 3000 fps at each of the 3 SD's (10 fps, 15 fps and 20 fps) to see how the hit percentage is affected. Table 16.9 shows the results for the IPSC target.

IPSC Silhouette at 1000 yards

	Hit % increase for SD improvement:	
	from 20 fps to 15 fps	**from 15 fps to 10 fps**
2600 fps Ave MV	74% to 83% (9%)	83% to 87% (4%)
3000 fps Ave MV	90% to 94% (4%)	94% to 94.5% (0.5%)

Table 16.9. How hit percentage is affected by improving SD for the IPSC silhouette at 1000 yards.

Note that for the 3000 fps average MV scenario, there is more improvement in hit percentage by reducing SD from 20 fps to 15 fps. In fact, the 15 fps to 10 fps improvement only yields 0.5% improvement on the IPSC target at 1000 yards. Considering the statistical nature of the model, that is essentially *no difference.*

10" Circle at 1000 yards

	Hit % increase for SD improvement:	
	from 20 fps to 15 fps	**from 15 fps to 10 fps**
2600 fps Ave MV	24% to 32% (8%)	32% to 39% (7%)
3000 fps Ave MV	42% to 51% (9%)	51% to 61% (10%)

Table 16.10. How hit percentage is affected by improving SD for the 10" circle at 1000 yards.

Now consider the same hit percentage improvements for the 10" circle target. You may be surprised to see a reversal in the trend! For the large IPSC target the increase in hit percentage was *more for the slower bullet.* But for the smaller 10" target, the hit percentage is improved *more for the faster bullet.*

The apparent contradictory information is explained quite easily.

For the large target/fast bullet scenario, the hit percentage is already so high (90%+) that it's difficult to improve on by improving MV consistency alone. Most of the misses in that scenario are due to wind anyway. However for the 10 inch target scenario, the hit percentage is much lower to begin with, and *many of the misses are due to vertical dispersion,* which is why improving SD has a stronger impact on hit percentage in that case. In other words, *if you're missing the target for reasons unrelated to vertical dispersion, then reducing vertical dispersion won't improve hit percentage very much.* In the case of the tall IPSC silhouette, very few of the misses are vertical. However for the 10" circle, many of the shots miss high or low.

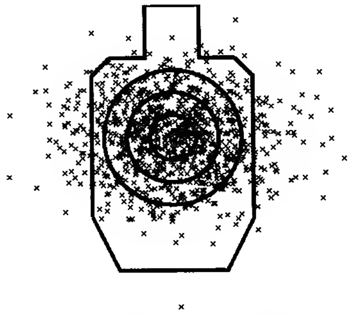


Figure 16.49. Majority of misses on the IPSC silhouette are due to windage, not elevation.

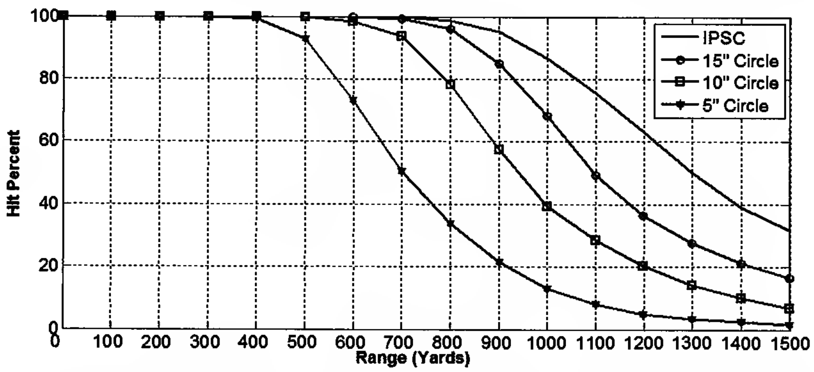
Figure 16.49 illustrates the point well. How much would you expect hit percentage to be improved on the IPSC target by reducing the *vertical* dispersion of the group? Not much because very few shots miss high or low. Now consider the 10" (medium) circle. It's easy to see that reducing MV SD (and hence vertical dispersion) would bring many of those shots within the 10" circle which are currently missing it.

This is a general principle that is true of all dispersion components and target sizes: *in order to improve hit percentage, you have to address those components of dispersion which are actually causing the shots to miss the target.* Seems like common sense, but without careful analysis, you might not know what dispersion elements are primarily causing you to miss.

Summary of muzzle velocity effects on hit percentage

- Higher average muzzle velocity improves hit percentage, but unless the muzzle velocity is *much* higher, the improvement is not great for most targets.
- Increasing the consistency of muzzle velocity does improve hit percentage thru minimizing vertical shot dispersion.
- The size and shape of the target will have a lot to do with how much MV SD affects hit percentage.

Hit Percentage for Muzzle Velcoity SD of 10 fps



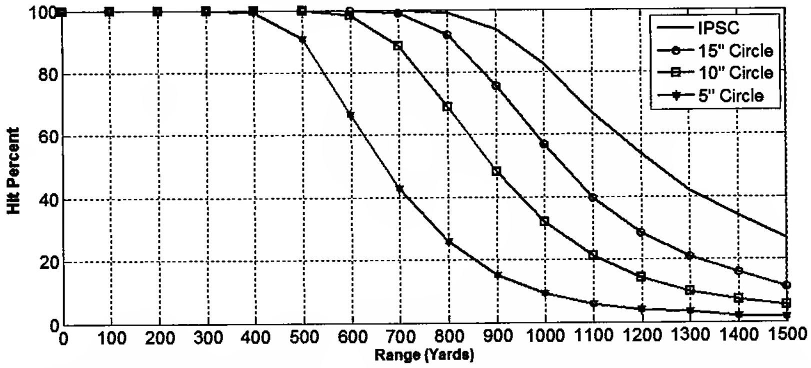
This WEZ was run for a high confidence set of environmental variables including the following:

Wind determination: +/- 1.0 mph
Range determination: +/- 1 yard
Rifle/Ammo precision: 0.5 MOA
Velocity consistency: 10 fps SD

Range Yards	5" Circle	10" Circle	15" Circle	IPSC
100	100%	100%	100%	100%
200	100%	100%	100%	100%
300	100%	100%	100%	100%
400	99%	100%	100%	100%
500	93%	100%	100%	100%
600	73%	99%	100%	100%
700	50%	94%	99%	100%
800	34%	78%	96%	99%
900	21%	57%	85%	95%
1000	13%	39%	68%	87%
1100	8%	29%	49%	76%
1200	5%	20%	37%	63%
1300	3%	14%	28%	50%
1400	3%	10%	21%	39%
1500	2%	7%	17%	32%

Figure 16.50. .30 cal 175 grain SMK (G7 BC = .243) at 2600 fps.

Hit Percentage for Muzzle Velcoity SD of 15 fps



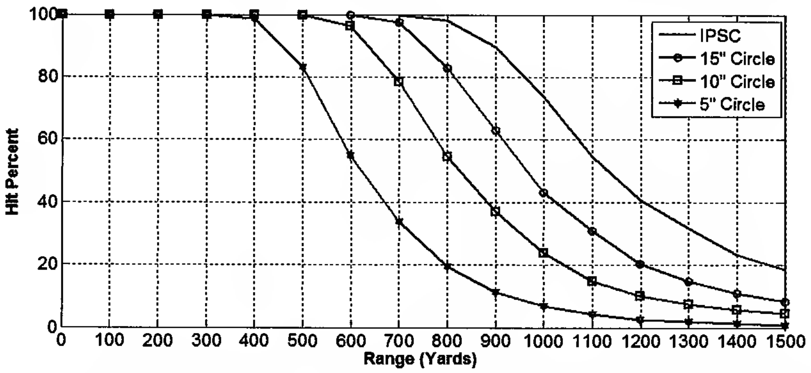
This WEZ was run for a high confidence set of environmental variables including the following:

Wind determination: +/- 1.0 mph
Range determination: +/- 1 yard
Rifle/Ammo precision: 0.5 MOA
Velocity consistency: 15 fps SD

Range Yards	5" Circle	10" Circle	15" Circle	IPSC
100	100%	100%	100%	100%
200	100%	100%	100%	100%
300	100%	100%	100%	100%
400	99%	100%	100%	100%
500	91%	100%	100%	100%
600	67%	98%	100%	100%
700	43%	88%	99%	100%
800	26%	69%	92%	99%
900	15%	48%	76%	94%
1000	9%	32%	57%	83%
1100	6%	21%	40%	67%
1200	4%	14%	28%	54%
1300	3%	10%	21%	42%
1400	2%	7%	16%	34%
1500	2%	5%	11%	27%

Figure 16.51. .30 cal 175 grain SMK (G7 BC = .243) at 2600 fps.

Hit Percentage for Muzzle Velcoity SD of 20 fps



This WEZ was run for a high confidence set of environmental variables including the following:

Wind determination: +/- 1.0 mph
Range determination: +/- 1 yard
Rifle/Ammo precision: 0.5 MOA
Velocity consistency: 20 fps SD

Range Yards	5" Circle	10" Circle	15" Circle	IPSC
100	100%	100%	100%	100%
200	100%	100%	100%	100%
300	100%	100%	100%	100%
400	99%	100%	100%	100%
500	83%	100%	100%	100%
600	55%	96%	100%	100%
700	34%	79%	97%	100%
800	20%	54%	83%	98%
900	11%	37%	63%	90%
1000	7%	24%	43%	74%
1100	4%	15%	31%	55%
1200	3%	10%	20%	41%
1300	2%	7%	15%	32%
1400	1%	6%	11%	23%
1500	1%	4%	8%	19%

Figure 16.52. .30 cal 175 grain SMK (G7 BC = .243) at 2600 fps.

Chapter Summary

This chapter examined the elements of precision in isolation including: wind uncertainty, range uncertainty, rifle/ammunition precision and muzzle velocity effects. All of this analysis was done assuming perfect accuracy, meaning centered groups. In this way, the analysis presented in this chapter can be considered *best case scenario* for hit percentage assessment, since it only gets worse if the groups come off center at all.

Although perfect accuracy is rare in the real world, this analysis is quite useful as it shows how you can miss even if you have perfect accuracy. In other words, most other published works on ballistics teach how to predict trajectories, and all the variables that influence a trajectory, etc. You can learn how to produce near perfect ballistic solutions, but how do you know what your chances are of hitting the target given the influences of dispersion? Shooters just *know* instinctively that the farther away and smaller their target is, the harder it is to hit, but really; what are the chances of hitting it? This is the question that this chapter answered for some nominal performance rounds. Of course hit percentages would be different for different rifles, ammo, environments, etc.

Another useful result presented in this chapter was the systematic study of field variables that cause dispersion. This taught us how much effect each variable has on hit percentage at various ranges, and against different sized targets. In other words, we explored the reasons for how and why lack of precision may cause us to miss targets.

Refer to Chapter 8 on using ballistics programs to learn more about the accuracy element; which is all about centering your group.

Part 3: Properties of Long Range Bullets

Chapter 17: Anatomy of a Bullet

This chapter will discuss the geometry, terminology, and physical nomenclature of external bullet design features and their effectiveness. The objective is to create an understanding of the various component parts of a bullet; what they're called and what purpose they serve.

The words *accuracy* and *precision* are used a lot in this chapter and it's important to remember what is meant by these terms. *Accuracy* is a measure of how close bullets impact to the center of the target. In other words, good accuracy results in high scores or a high probability of hit. *Precision* is a measure of how close bullets can group to each other; so good precision results in small groups. Most considerations involving bullet design deal with precision, not accuracy. Accuracy is determined more by the shooter, his understanding of bullet trajectory, and having control of the sights.

This chapter makes common use of the *caliber* as a unit. When used in this way, the unit caliber means one bullet diameter. For example, if I'm talking about a .30 caliber bullet and I say the boat tail is 0.8 calibers long, that means the boat tail is 0.8 times 1 caliber, or 0.8 *.308" = 0.246" long.

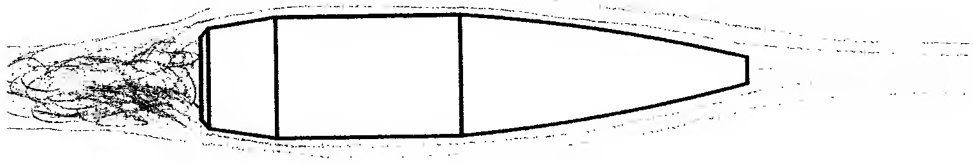
Boat-tails

A properly designed boat-tail can increase the BC of a bullet by decreasing base drag. There is a low pressure area at the base of the bullet as it travels thru the air at high speed. That low pressure region (vacuum) behind the bullet is applied to the area on the base of the bullet and results in base drag. *The goal of a boat tail is to reduce the effective base area to which this vacuum applies.*

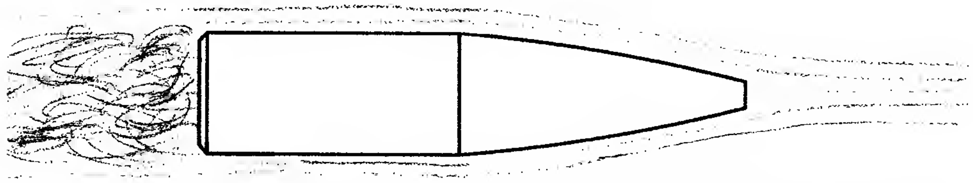
Tapering the back of a bullet allows the air to flow along the boat-tail before separating off the reduced diameter base. The boat-tail produces a smaller base area for the low pressure to act on, thereby reducing base drag.

There are some limitations to what you can do with boat-tails. One common instinct is to make the boat-tail longer, the idea being to further reduce the base area and base drag. The reason why extra long boat-tails don't work is because they compromise the dynamic stability of the bullet. A boat-tail length of around 0.8 calibers is the practical maximum length for boat-tails on spin stabilized projectiles. Another common thought is to increase the angle of the boat-tail so that the base area is decreased for the same length boat-tail. However, as noted above, air flow separation limits how steep the boat-tail angle can be. Imagine if you make the boat-tail very steep, 45 degrees for example. The air flow will not follow the boat-tail and separate off the base. Instead it will separate at the body/boat-tail junction. In that case, the bullet acts just like a flat base with separated flow and the suction is applied to the entire cross sectional area of the bullet. Tests have shown that the optimal angle for boat-tails is around 7-8 degrees.

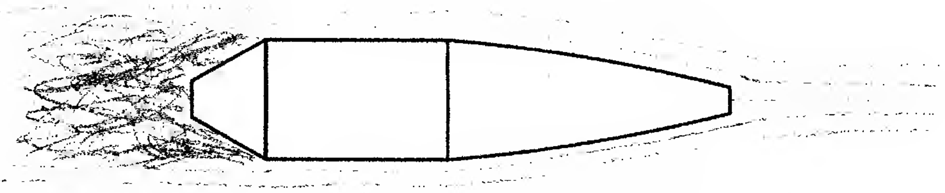
Air Flow Separation and base drag reduction



A properly angled boat tail allows the airflow to remain attached to the surface until it reaches the reduced diameter base. As a result, the low pressure (suction) will apply to a smaller area at the base of the bullet and result in less base drag.



On a flat base bullet, the air flow simply separates from the bullet body and the low pressure is applied to the entire base of the bullet resulting in maximum base drag.



If the boat tail is too steep, the air flow will not remain attached and will separate off the bullet body just as if it were a flat base. No base drag reduction is accomplished with a boat tail that's too steep (more than about 20 degrees).

Figure 17.1. Effect of different boat tail angles on air flow separation

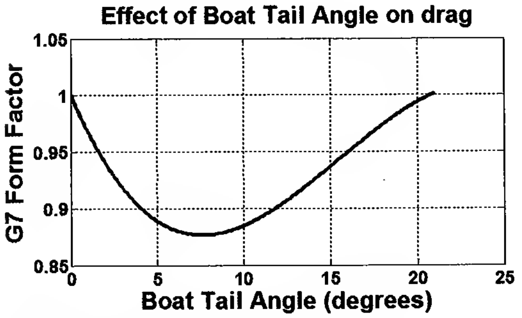


Figure 17.2. Drag reduction of a 0.7 caliber long boat tail.

Figure 17.2 shows the drag reduction for a 0.7 caliber long boat tail for the range of angles between 0 and 21 degrees. Notice that drag is minimized for a boat tail angle of about 7-8 degrees. This is true for any length of boat tail at supersonic speeds.

Boat-tails help out more at lower speeds (1500 fps to 2500 fps) than at higher speeds (3000 fps+). That's because at higher speeds, the strong shock wave generated at the nose of the bullet is responsible for most of the overall drag. As the bullet slows down, the shock wave weakens, and base drag becomes a more significant component of overall drag. For this reason, the benefits of boat-tail bullets are more pronounced at longer ranges than short range. Sometimes this fact is misinterpreted as "boat tails *only* help at low speed". The truth is, boat tails reduce base drag and increase BC at all speeds, but their effect is proportionally greater at lower speed. Regardless of how you interpret the fact, a well designed boat tail is an important asset for long range bullets.

Boat-Tails and precision

Boat-tail bullets are inherently less precise than flat base bullets for several reasons. First of all, the added steps in making boat-tail bullets allow more potential for imperfections like making the boat tail off center. Modern manufacturing practices minimize the imperfections, but the bottom line is that forming a boat-tail is an extra step that can potentially introduce misalignment and mass imbalance.

Furthermore, muzzle blast effects are more detrimental to boat-tail bullets than flat bases because the boat-tail offers a surface that's nearly parallel to the bullet axis for the escaping high pressure turbulent gases to buffet, which can cause the bullet to pitch and yaw early in flight.

Finally, boat-tails affect the mass properties and aerodynamics of a bullet in a way that causes them to require higher twist rates to stabilize. Since many components of dispersion are proportional to spin rate in some way, increasing spin rate has a negative impact on precision potential. The difference in accuracy potential between boat-tail bullets and flat bases is very small. *The reason why we use boat-tails is because at extended ranges, the aerodynamic benefits overcome atmospheric variations better than flat bases, and make up for the marginally compromised precision potential.* The net result is smaller groups at longer ranges. Over short range, the ballistic performance advantage of a boat tail is not enough to make up for it being less inherently precise.

Rebated boat-tails are boat-tails that have a step down in diameter from the bullet body to the start of the boat-tail, and taper to the base from there. There are many claims about the advantages of rebated boat tails related to accuracy and BC. I don't believe a rebated boat tail makes a bullet any more or less precise than a conventional boat tail.

Figure 17.3. Rebated boat-tail bullet.

As for drag reduction, there's no way a rebated boat tail can reduce base drag any more than a conventional boat tail of equal length and angle. In fact there is a potential for the rebated boat-tail to compromise the *boat-tail effect* by causing flow separation if the step is too big. How big is too big depends on the caliber among other things. Makers of rebated boat-tail bullets claim 0.015" step is *not too bad.* This step size happens to be the smallest step that can be reliably made with typical custom dies. Most claims about rebated boat-tail bullets are unsubstantiated. My BC testing indicates no advantage in drag reduction compared to conventional boat tail bullets of similar length and angle. I haven't compared them to conventional boat tail bullets for precision. There are so many variables of bullet design related to precision and it would be difficult to isolate the effect of the rebated boat tail.

Bullet Nose Profiles

The nose of the bullet is technically called the *ogive*, and is pronounced O-jive. Almost all ogives are circular arcs. The circular arc will either be *tangent* to the bearing surface or *secant* to the bearing surface. If the arc joins the bearing surface smoothly, it's called a *tangent* ogive. If there is a visible, abrupt junction between the bearing surface and ogive, then the ogive is *secant.* Most of the Sierra MatchKing bullets, Nosler Ballistic Tips, and Berger BT bullets use tangent ogives. Examples of secant ogive bullets are the Berger VLD, Hornady Amax and Vmax, and some Lapua Scenars.

The ogive of a bullet is usually characterized by the length of its radius. This radius is often given in calibers instead of inches. For example, an *8 ogive* 6mm bullet has an ogive that is a segment of a circular arc with a radius of 8*.243 = 1.952". A .30 caliber bullet with an 8 ogive will be proportionally the same as the 8 ogive 6mm bullet, but the actual radius will be 2.464" for the .30 caliber bullet.

For a given nose length, if an ogive is perfectly tangent, it will have a very specific radius. Any radius longer than that will cause the ogive to be secant. Secant ogives can range from very mild (short radius) to very aggressive (long radius). The drag of a secant ogive is minimized when its radius is twice as long as a tangent ogive radius. In other words, if a tangent ogive has an 8 caliber radius, then the longest practical secant ogive radius is 16 calibers long *for a given nose length.*

There is a number that's used to quantify *how secant* an ogive is. The metric is known as the Rt/R ratio and it's the ratio of the tangent ogive radius to the actual ogive radius for a given bullet. In the above example, the 16 caliber ogive would have an Rt/R ratio of 0.5. 0.5 is therefore the lowest practical value for the Rt/R ratio, and represents the minimum drag ogive for a given length. An ogive that's perfectly tangent will have an Rt/R ratio of 1.0. Most ogives are in between an Rt/R of 1.0 and 0.5. The dimensioned drawings published in *Ballistic Performance of Rifle Bullets* provide the bullets ogive radius in calibers, as well as the Rt/R ratio. *In short, the Rt/R ratio is simply a measure of how secant an ogive is. 1.0 is not secant at all, 0.5 is as secant as it gets.*

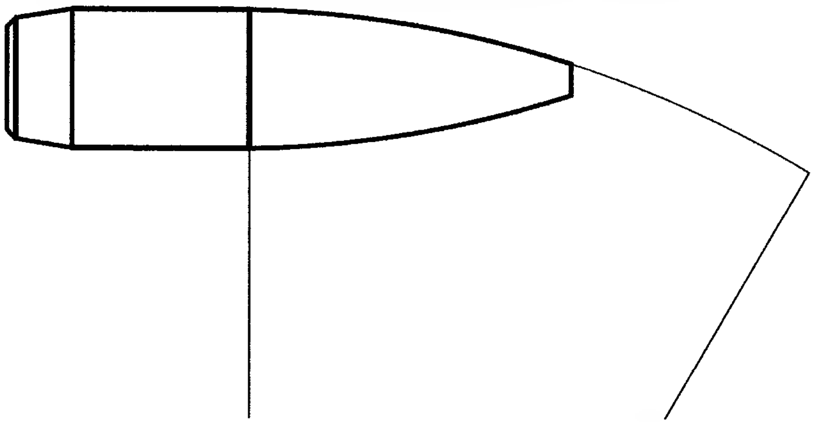
The length and contour of the bullets ogive are the two most important factors in how much drag the bullet will have. The drag of the ogive is determined by how much energy is required to *shock* the air into a compression wave as the bullet travels supersonically. In other words the nose acts as a wedge. Its job is to make way for the bullet to move thru the air. The most efficient ogive is the one that requires the least amount of energy to *shock* the air into a compression wave. The difference in drag between tangent and secant ogives can be up to 12% in favor of the secant ogive (if they're the same length).

Ogive length can be even more important than shape. The difference in drag between a 2 caliber long ogive and a 3 caliber long ogive is around 25%. The best way to minimize shock wave drag is to lengthen the ogive. Careful design of the ogive pays the greatest dividends when the bullet is flying fast because at high speeds, the greatest contributor to drag is shock wave drag from the nose. As with boat-tails, stability sometimes limits the practical length for an ogive, not to mention the difficulties involved in forming such long points out of copper. Jacket drawing, lubrication and ejection from bullet pointing dies become a challenge for bullets with long ogives.

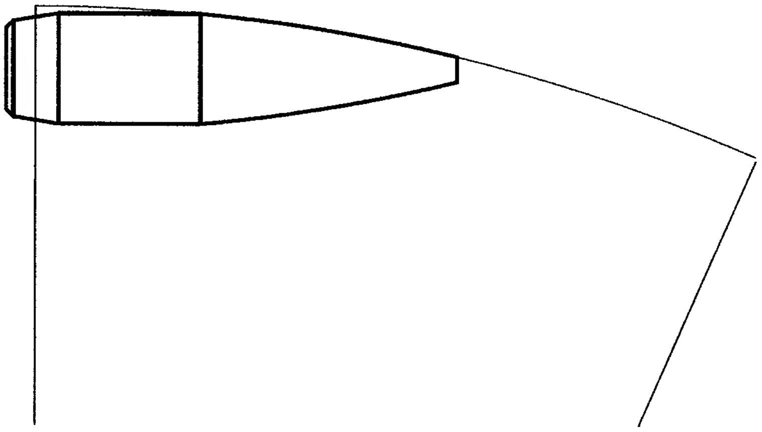
Bullets with secant ogives are known to be *finicky* in relation to bullet seating depth. A popular notion is that the more abrupt nose/body junction for the secant ogive doesn't self-align itself in the riflings as well as a tangent ogive bullet. A common solution is to soft seat the secant ogive bullets into the lands, thereby eliminating bullet jump, and minimizing the potential for misalignment as the bullet starts down the barrel. One may calculate the proper leade angle for a particular bullet's ogive design and have the leade cut to match. However, the leade angle is one of the first dimensions to erode as the barrel wears. Consequently, the carefully designed and cut leade angle quickly becomes irrelevant.

Another potential precision limiter of the secant ogive design has to do with the severe shaping of the jackets in the ogive. It's harder to make secant ogive bullets without wrinkles near the nose. These wrinkles are caused by lubrication, similar to the lube dents that appear on the shoulder of a brass casing if too much lube is used when resizing. These *lube lines* are a potential source of mass imbalance. Good quality copper jackets are required to make consistent wrinkle free secant ogives. The wrinkles, and the potential imbalance associated with them are less of a problem for tangent ogive bullets.

Bullet Ogive profiles are sections of circular arcs



A tangent ogive is a circular arc that joins the bearing surface smoothly (above).



A secant ogive causes an abrupt transition between the circular arc and the bearing surface (above)

Figure 17.4. Tangent and secant ogives.

The comparison of precision between secant vs tangent ogives is pretty much the same as boat-tails vs flat base. The secant ogive may not have the inherent precision of a tangent ogive, but at long range the superior aerodynamic design of the secant ogive helps the bullet overcome atmospheric variations better, and usually result in smaller groups at long range as a result. At short range, the atmospheric effects aren't as dominant, and BC can be compromised for inherent precision.

Berger's *Hybrid* ogive

Given the properties of the traditional tangent and secant ogive designs described above, it seemed only a matter of time before someone figured out a way to combine the positive attributes of both types of ogives (tangent and secant). Berger Bullets has done exactly that in their new line of *Hybrid* ogive bullets. Figure 17.6 summarizes the strengths and weaknesses of the traditional tangent and secant ogives, and shows how the hybrid ogive combines the best of both worlds, so to speak.

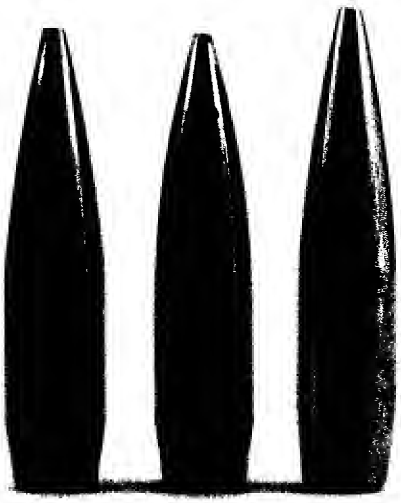
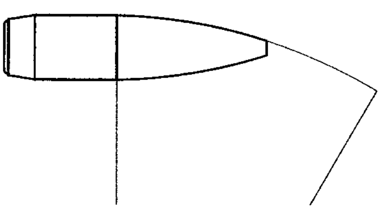
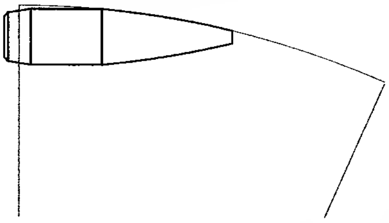


Figure 17.5. From left to right: secant, tangent, hybrid.

To the left in Figure 17.5 you can see a photograph of 3 .30 caliber bullets, all 185 grain. On the far left is the secant ogive which Berger calls the VLD. Note the abrupt transition from bearing surface to ogive as evidenced in the light reflection. The middle bullet is a pure tangent ogive. Again, note how the reflection indicates a very smooth junction from bearing surface to ogive. Finally on the far right is the hybrid ogive which you can tell blends gradually at first, then transitions to a longer (lower drag) radius.

This author originated the hybrid design concept for Berger bullets. However *dual radius* ogives are not a completely novel idea. In fact, there are many possibilities for ogive shapes, some of them are much more sophisticated than circular arc sections. Some examples of these optimized shapes are the Von Karman and Sears-Haack ogives which are named after their developers, and the 3/4 power and parabolic ogives which are named for the geometric shapes that they're made from. Each of the *optimal* ogive types have different speeds for which it's best.

Many of the CNC lathe turned solid bullets can take advantage of these more sophisticated nose profiles because of the flexibility and precision available in the machining process. On the contrary, most dies used to make conventional (jacketed lead core) bullets are limited to tangent or secant ogive shapes. The basic secant ogive can be considered a practical minimum drag nose shape at supersonic speeds **[REF 1]**.

Tangent Ogive		**Secant Ogive**	
			
Strength	**Weakness**	**Strength**	**Weakness**
Smooth juncture with bearing surface is good for self aligning the bullet into the riflings, thereby making the bullet less sensitive to seating depth and therefore is ***easy to find and maintain precision.***	The tangent ogive has ***more drag*** (lower BC) than a secant ogive (VLD) of the same length.	***Lower drag*** (higher BC) than a tangent ogive of the same length.	The abrupt juncture between the bearing surface and ogive is not good for self-aligning the bullet in the riflings so this shape is quite sensitive to seating depth and is therefore more ***difficult to find and maintain precision.***

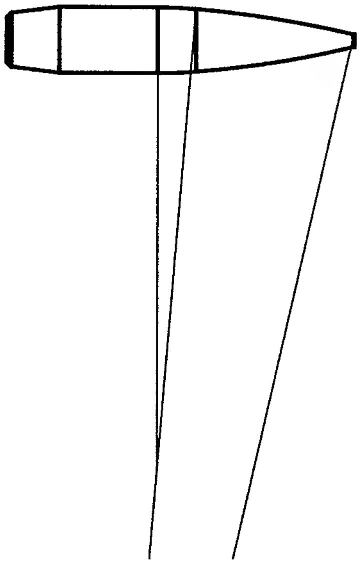
Hybrid Ogive	
	The *Hybrid* ogive combines the strengths of both the tangent and secant ogives, without suffering either of the weaknesses. The Hybrid ogive is tangent to the bearing surface *where it contacts the riflings*. This aids the bullet in self-aligning with the bore and making it less sensitive to seating depth. Forward of the point where the riflings engrave the bullet, *the ogive transitions into a longer radius (lower drag) ogive* which is good for drag reduction. ***The end result of the Hybrid ogive is a bullet with the low drag/high BC of a secant ogive (VLD) which also accomplishes precision easily in many rifles because it's not sensitive to seating depth.***

Figure 17.6. The hybrid ogive combines the strengths and weaknesses of the traditional tangent and secant ogive designs.

Meplat considerations

The *meplat* is just another word for the flat or open tip of the bullet. The meplat on match bullets is typically a rough, flat opening as seen in Figure 17.7. This shape is a result of the bullet making process. The copper jacket starts out as a cup. Then the lead core is pressed into it. A boat-tail is then formed, and finally the bullet is forced into the pointing die. In order to eject the bullet from the pointing die, an ejection pin pushes on the tip of the bullet. The diameter of the meplat has to be large enough to withstand the pressure of the ejection pin. If the ejector pin is too small, it can break leaving a bullet stuck in the pointing die. The size requirement of the ejector pin is the fundamental limiting factor of how small a bullet's meplat can be made.

Several meplat treatments are becoming popular among long range shooters these days including the following items.

Figure 17.7. Meplat

Meplat Trimming

The idea behind trimming meplats is to remove the inconsistency of the tips. If you look closely at the meplats within a box of bullets, you'll notice that the ragged tips are not all the same. Meplat trimming is the act of cutting the meplats so they're smooth and all the same diameter.

Meplat trimming can be a subject of hot debate. Some swear that the practice is absolutely necessary for everyone in every shooting situation. Others contend that the improvement is so small that only the highest level Benchrest shooters can notice a difference. The potential benefit of meplat trimming is to produce bullets with uniform BC, and thereby minimize vertical dispersion. The benefit you are likely to see depends on how bad the bullets were to begin with, and how well you can shoot with your equipment and shooting style (prone, F-class, bench, etc). As a general rule, you can say that if you're already shooting very small groups, and you're looking for that last bit of improvement, it may be worth the time to trim (uniform) your meplats. However, if you're grouping larger than 1 MOA to begin with, you're unlikely to see a significant benefit from meplat trimming. An important thing to keep in mind is not to over trim the meplat. The benefits of uniformity might not outweigh the gross reduction in BC if you flatten the tips too much. If done properly, trimming the meplats should only reduce the average BC of a bullet by ~2% to 3%.

Meplat Pointing

Pointing meplats is a relatively new option whereby bullets are run into a special die and the meplat is *squeezed* down to a smaller diameter. The idea here is twofold: First, the reduced diameter meplat *increases the BC.* Furthermore, the effects of irregularities in the meplat are minimized, so you have a *more uniform BC* as well. You can expect more of a benefit for pointing meplats on smaller caliber bullets for several reasons: First, because smaller caliber bullets generally fly faster than larger ones. For faster bullets, wave drag from the nose is a more significant contributor to overall drag.

Various Aftermarket Meplat Treatments

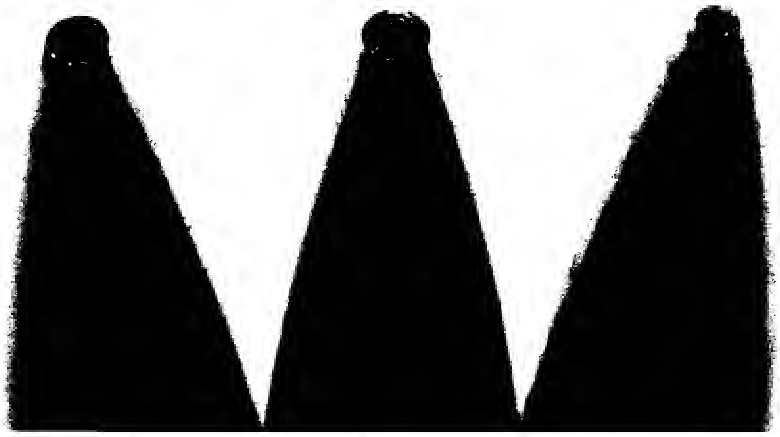


Figure 17.8. Unmodified, trimmed and pointed meplats.

Reducing the diameter of the meplat greatly reduces the wave drag of the nose. Secondly, the meplat of smaller caliber bullets is proportionally larger than for bigger calibers. For example, a 0.060" meplat on a .22 caliber bullet is 27% of the bullet's diameter. However, that same 0.060" meplat on a .30 caliber bullet is only 19% of the bullet's diameter. Bottom line: meplat pointing helps smaller caliber and faster bullets more than larger caliber slower bullets.

There is a potential pitfall to pointing bullets. Since the bullets are supported from the base during the pointing process, the success of the operation depends on bullet length consistency. In other words, shorter bullets won't be pointed as much as longer bullets for a given die setting. This could lead to higher but not perfectly consistent BC's.

"Should *You* Trim and/or Point Meplats?"

It's a big question for many shooters, especially competitors who are looking for any edge in ballistic uniformity and consistency. The answer is: *It depends.* Specifically, it depends on the nature of the meplats out of the box. If you have a box/lot of bullets with very small and consistent meplats, you're unlikely to gain any noticeable advantage by trimming or pointing. However, if your bullets have large but consistent meplats, then just pointing them will yield the best returns. Finally, if your lot of bullets have meplats that are large *and* inconsistent, then it may be worth it to trim and point the bullets.

The general approach should be to allow yourself the flexibility to decide on trimming/pointing based on the characteristics of your particular batch of bullets. As with many things, applying a blind *do or do not* policy is probably not best when considering meplat treatments.

Plastic Tips

Plastic tipped bullets like the Nosler Ballistic Tip and Hornady Amax/Vmax bullets solve several problems associated with meplats. First, it's possible to make the plastic tip a little *pointier* than a copper meplat. The effective diameter of most plastic tipped bullets is around 0.040", which isn't a lot smaller than a well formed meplat on conventional open tip bullets. The drag reduction of plastic tip bullet is real, but amounts to less than is commonly thought. An average plastic tipped bullet will have about as much drag as a meplat that's been properly pointed to a 0.040" diameter.

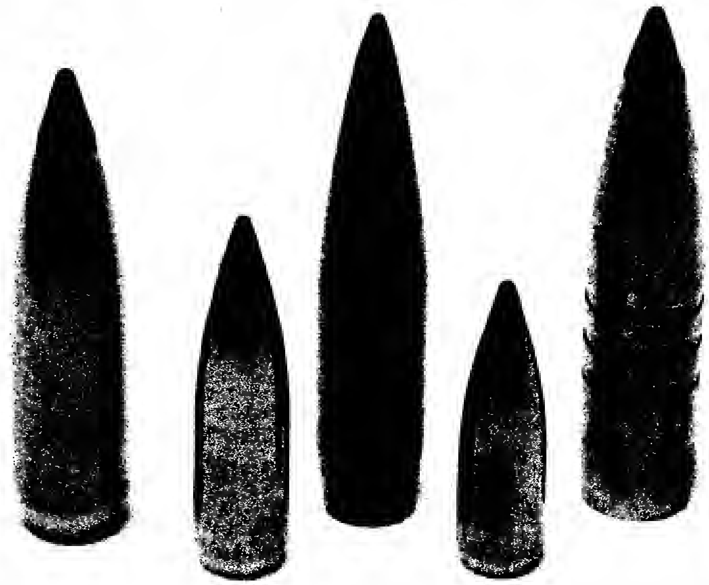


Figure 17.9. Plastic Tip bullets. From left to right: Nosler 30 caliber 165 grain Ballistic Tip, Nosler 6mm 80 grain Ballistic Tip, Hornady 7mm 162 grain Amax, Nosler .22 caliber 55 grain Ballistic Tip, Barnes .30 caliber 168 grain TTSX Boat Tail.

The plastic tips are easier to keep uniform than conventional open tip bullets. It's easier to eject the metal part of the bullets from the dies because they're not being pointed down to such a small diameter. The drawback of making plastic tipped bullets is that it adds another component, and another step to the bullet making process. In a process where consistency is paramount, fewer steps are always better.

Chapter 18: Monolithic Bullets

The term *Monolithic Bullet* typically refers to bullets that are not made of the typical lead core and copper jacket. Although monolithic implies only one material, it's quite common for these bullets to have other materials like plastic tips, and sometimes cores of higher density material. Most monolithic bullets used in long range shooting are turned on a lathe. Barnes is the only exception to this that I know of.

Monolithic bullets are often referred to as *Solids*. Solid bullet construction has certain advantages and disadvantages compared to copper jacket/lead core (hereafter referred to as *conventional* construction) bullets.

Advantages of monolithic bullets

One of the biggest differences between solid and conventional bullet construction is the way they behave terminally (on impact) with game. Conventional bullets made of softer materials will expand and fragment to some degree on impact. Solid bullets can be designed to stay in one piece, retaining 100% of their original weight, regardless of impact speed. Furthermore, they can be made to break apart in a very predictable way by machining open tips and scribing stress lines into the tips of the bullet. A higher percentage of weight retention will result in deeper penetration for a given bullet weight, caliber, and impact speed. Of course there is the opposing school of thought which advocates that a rapidly expanding/fragmenting design is more lethal than a deeper penetrating one,

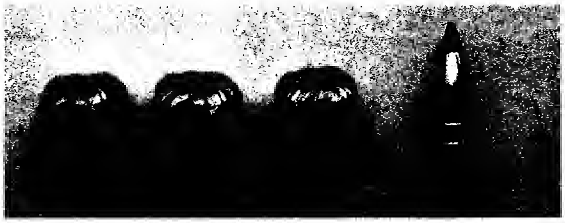


Figure 18.1. Solid bullets have very consistent expansion characteristics and can retain close to 100% of their weight.

but that debate is not within the scope of this chapter or book on external ballistics.

Another advantage of solid/monolithic bullets has to do with the manufacturing options that are possible by producing them on a lathe. Conventional bullets are swaged in dies. Those dies are expensive, take a long time to fabricate, and can only produce one shape of bullet. If you wanted to make a small change to the design of a conventional bullet, you have to incur the cost and wait for the new die to be made. With lathe turned bullets, you can program a CNC machine with a computer generated design and the lathe immediately produces that shape. If you want to make a small change, it's a simple matter of changing the computer drawing, reprogramming the CNC lathe, and you have another shape. This capability is very useful when a new bullet is being prototyped. You can literally produce a test run of 100 bullets in the morning, test fire them in the afternoon, and make adjustments for the next iteration of the design tomorrow.

In addition to the flexibility of manufacturing bullets on a lathe, it's also possible to create more radical shapes than conventional bullets. Conventional bullets have limits to how long and narrow a nose can be before the jacket cracks or folds. This is not a limitation for lathe turned bullets.

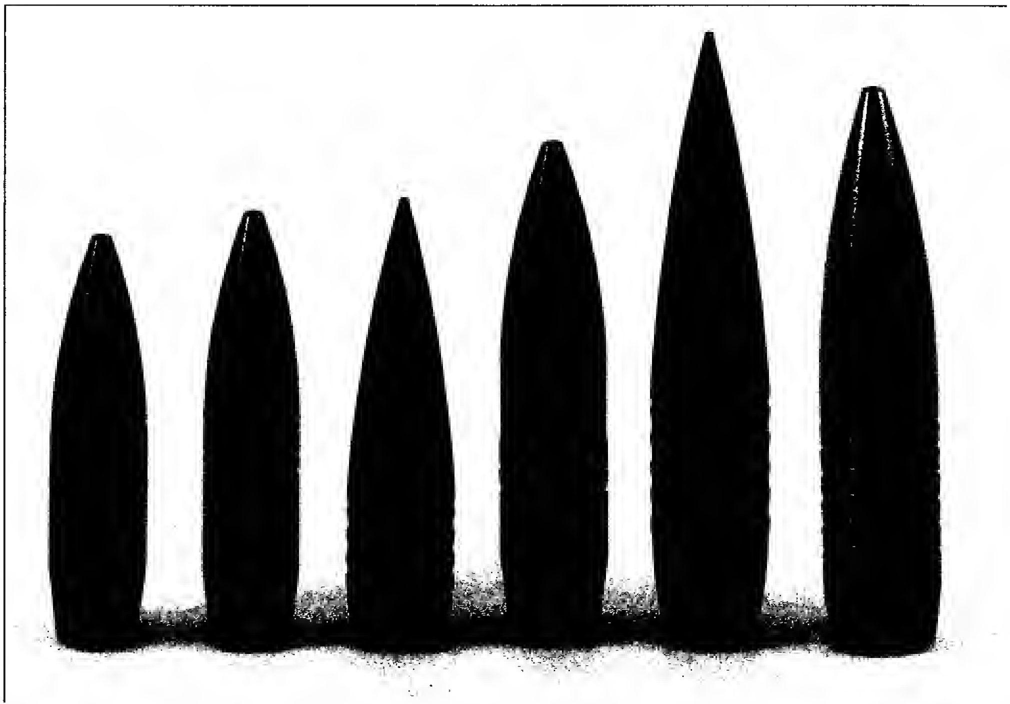


Figure 18.2. Lathe turned monolithic bullets. From left: Cutting Edge .270 caliber 120 and 130 grain, GS Custom .30 cal 137 grain SP, Cutting Edge .30 cal 180 grain, GS Custom .338 cal 237 grain, Lehigh .338 cal 230 grain.

Another advantage that's possible with lathe turned solids is the ability to make a needle sharp point (notice the GS custom bullets in the above photo). Conventional bullets will always have a flattened tip which is necessary for the ejector pin to push the bullet out of the point forming die in the swaging operation.

A final advantage that's possible with lathe turned bullets is the ability to create relief grooves and/or drive bands on the bearing surface. Monolithic bullets have to be longer than conventional bullets of the same weight, a consequence of being made from less dense materials. As a result, the bearing surfaces can get quite long, which causes internal ballistics problems like excess fouling, accelerated barrel wear, and reduced MV from additional in-bore friction. The drive bands and relief grooves address these problems by reducing the surface area that contacts the bore. The grooves can be made in such a way as to reduce the contact area to be less than that of a conventional bullet, and result in increased MV for the same pressure (thru the reduction of friction).

Disadvantages of monolithic bullets

Just about every disadvantage of monolithic bullets stems from the reduced density of the material they're made from. Copper, which is the material most commonly used in monolithic bullet construction, is about 23% less dense than lead. Other materials such as brass are even less dense. That means that to make a bullet of the same weight as a conventional bullet, the monolithic bullet has to be somewhat longer. They don't end up being 23% longer because conventional bullets do have a significant amount of copper in their jackets, and many have a hollow cavity in the nose as in the case of open tip bullets which reduces their effective density below that of pure lead. On average, monolithic bullets tend to be at least 10% longer than conventional bullets of the same weight. Refer to figure 18.3 for a comparison of .30 caliber 180 grain bullet lengths. More examples can be found in .338 caliber. The GS Custom 232 grain SP copper bullet, and the Lehigh 230 grain brass monolithic bullets are 1.771" and 1.608" in length, respectively. The 250 grain Lapua scenar and Sierra MatchKing bullets are 1.551" and 1.567" long. So in this case, the

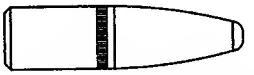
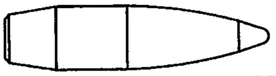
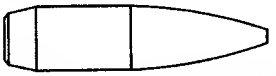
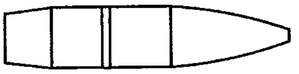
Bullet	Length
 *Nosler 180 Partition*	1.188"
 *Sierra 180 Game King*	1.287"
 *Sierra 180 Match King*	1.277"
 *Cutting Edge 180 HPBT*	1.458"

Figure 18.3. The Cutting Edge 180 grain solid copper bullet is quite longer than the other 180 grain .30 caliber bullets.

heavier conventional bullets are quite shorter than the lighter monolithic bullets.

The following specific disadvantages of monolithic bullets all have to do with their additional length.

Lengthening a bullet while keeping it the same weight will result in *less gyroscopic stability* for a given twist rate. This isn't as big of a problem for light and medium weight monolithic bullets, because they can still be stabilized in conventional twist barrels. However, if a monolithic bullet is to match the weight of the *heaviest* conventional bullets in a given caliber, the monolithic bullet has to be *so long* that it cannot be stabilized in conventional twist barrels. It is possible to have barrels made with abnormally fast twist rates (like 1:7" or 1:8" for .30 cal and .338), but those barrels are not likely to shoot conventional bullets very well. They might even cause conventional bullets to fail if fired at high enough MV. This means that you need a barrel dedicated to a specific monolithic bullet, or narrow range of bullets, if you want to shoot the heaviest monolithics. Note, this only applies for monolithic bullets that are as heavy as the heaviest conventional bullets.

The length/stability consideration is also important to the bullet's ability to remain stable thru transonic speeds. Where some conventional bullets can remain stable depending on their design, it's very uncommon for a monolithic bullet to remain stable thru transonic due to the extra length of the bullet. Exceptions would be large caliber, light to medium weight monolithic bullets fired from fast twist barrels at high altitude. In other words, all the variables have to be in favor of stability in order to overcome the de-stabilizing effects of the reduced density bullets.

Ballistic performance of monolithic bullets: theory meets reality

One needs only to look at the long, sleek, shiny lathe turned bullets and the imagination runs wild about how high the BC must be. Computer estimated BC's are off the charts and that begins endless debates about the potential performance of monolithic bullets. As you'll find with most things that sound *too good to be true,* they usually are.

My first BC test of a lathe turned bullet produced very poor results. The stability of this particular bullet was in question from the barrel I fired it from, so I chalked up the poor performance to inadequate stability and disregarded the test. Next I acquired some light to medium weight samples of lathe turned bullets from 3 manufacturers, shown in figure 18.2. These were all tested in barrels that have adequate twist to stabilize them according to the manufacturer's suggestions, and my own calculations. The firing tests that followed were properly conducted, and repeated results for other bullets that have been tested many times. ***In every test, the lathe turned bullets had measured BC's that were much lower than one would expect from computer predictions based on their shapes.***

Figure 18.4 summarizes the results of the BC tests for the lathe turned bullets, compared to the advertised BC's.

You'll notice that the G1 BC's vary a lot for those bullets that have banded G1 BC's. For example, the G1 BC for the GS Custom 137 grain SP goes from .290 at 1200 fps to .478 at 3800 fps. That's a variation in G1 BC of over 60%! Due to the extremely long ogives, non-conical boat tails, needle point noses and drive bands, most of the lathe turned solids have drag curves that don't even match the G7 standard curve very well, and bear no resemblance at all to the G1 curve. In order to accurately model the performance of bullets that are shaped like this, the use of a custom drag curve is necessary, even within the supersonic range of bullet flight. Using G1 BC's that vary by up to 60% over the normal range of flight speeds is a very poor way to model the performance of these kinds of bullets.

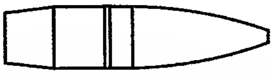
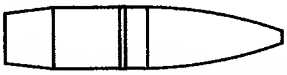
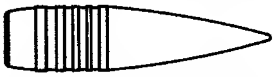
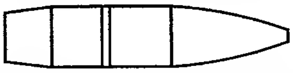
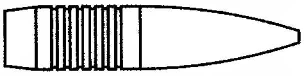
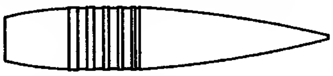
Bullet	Advertised G1 BC	Measured G1 BC	Error
 *Cutting Edge 120 HPBT*	0.460	0.408	-13%
 *Cutting Edge 130 HPBT*	0.540	0.444	-22%
 *GS Custom 137 SP*	3800 fps: 0.530	0.478	-11%
	2500 fps: 0.426	0.402	-6%
	1200 fps: 0.290	0.290	0%
 *Cutting Edge 180 HPBT*	0.600	0.478	-26%
 *Lehigh 230 brass solid*	0.641	0.552	-16%
 *GS Custom 232 SP*	3300 fps: 0.824	0.689	-20%
	2250 fps: 0.731	0.602	-21%
	1200 fps: 0.525	0.458	-15%

Figure 18.4. G1 BC's vary greatly over the flight envelope of the radically shaped lathe turned bullets. It's also common for estimated performance to be far in excess of measured performance.

Along with the variation in G1 BC, Figure 18.4 also shows that in most cases, the advertised BC's are much higher than the measured ones. The Cutting Edge and Lehigh bullets only give a single G1 BC without saying what velocity it applies for. The measured G1 BC is the average value from 3000 to 1500 fps. The advertised G1 BC might be accurate for some very high muzzle velocity, but not for the average velocity of a long range trajectory. The velocity dependence of G1 BC's is covered well in Chapter 2, so I won't go into any more detail here. Suffice it to say that a single G1 BC for radically shaped bullets is next to useless.

There are several reasons why the predicted performance of lathe turned bullets usually exceeds the actual, measured performance. One reason is related to the extra length of the bullets. A longer bullet has more *wetted area* (area exposed to air friction) than a shorter bullet. The increase in wetted area means more skin friction drag for the longer bullet.

Another feature of the lathe turned bullets that affects drag is the drive bands. The drive bands create shock waves that don't exist for conventional bullets, and also add further to the skin friction drag of the bullets.

To illustrate the statements in the previous two paragraphs, compare the .270 caliber Cutting Edge designs to the GS Custom .308 and .338 designs. The Cutting Edge bullets do not have excessively long noses or boat tails, so their skin friction drag is not elevated much above that of a conventional bullet. On the contrary, the GS Custom bullets are very long for their caliber and weight. Furthermore, the Cutting Edge bullets have only one drive band as opposed to 4 or more on the GS Custom bullets. As a result of these differences, it's interesting to note that the measured G7 BC of the Cutting Edge bullets is only 5% lower than the estimated G7 BC for the same velocity range (3000 to 1500 fps). However, the measured G7 BC of the GS Custom bullets is at least 20% less than the estimated BC for the same velocity range (3000 to 1500 fps).

The point of the preceding analysis is to show that performance estimations of lathe turned bullets can be very optimistic compared to actual test results.

Of course there are many other lathe turned bullets to choose from and I haven't tested them all. However my analysis indicates that there are likely reasons for the estimated performance of all lathe turned bullets to usually be higher than the actual performance, in some cases, very much higher.

This is not to say that the performance of monolithic bullets is bad. In fact, the BC's of all the Cutting Edge BTHP designs tested are on par with average hunting bullets of the same weight. The GS Custom 232 grain .338 caliber bullet has a G7 form factor of 0.939, which is extremely low drag, in fact it's the second lowest drag .338 bullet tested. So the performance of the lathe turned bullets isn't necessarily bad, it's just likely to be overestimated by most prediction methods. For that reason, careful testing of these bullets to develop banded BC's (better yet, full custom drag curves) is absolutely necessary in order to achieve reliable trajectory predictions at long range.

The final disadvantage of monolithic bullets is also related to them being made of less dense material, and being longer. Consider a conventional bullet loaded to magazine length in any given cartridge compared to a longer monolithic bullet. ***The rear end of the longer monolithic bullet will take up more internal case capacity than a conventional bullet when loaded to the same cartridge overall length (COAL).*** This is important because the internal case capacity is related to how much powder you can load in the round, and what max velocities can be achieved with the cartridge.

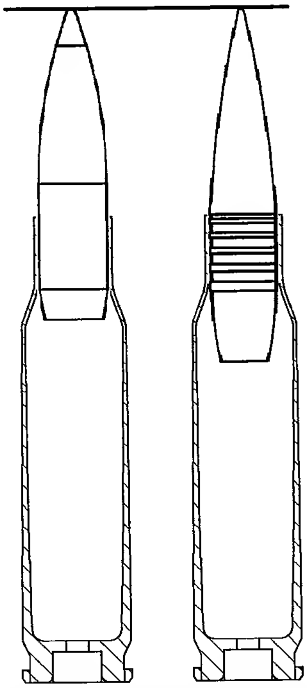


Figure 18.5. The lower density, longer monolithic bullet takes up more internal case capacity when loaded to the same COAL compared to a conventional bullet.

This is only an issue if a shooter is limited on what their max COAL can be, as in the case of magazine feeding. If a shooter single loads their rounds, and uses a chamber that's throated to allow a specific bullet to be seated out of the case, then this is a non-issue.

Summary

The following list summarizes the pros and cons of monolithic bullets:

Pros

- Better penetration and weight retention due to solid construction of harder materials.
- Manufacturing on CNC lathes enables very effective and flexible prototyping of designs.
- Drive bands and relief grooves on the bearing surface are possible.
- Machining the nose down to a needle point is possible.

Cons

- Lower density materials are bad for stability; heavier monolithic bullets require radical twist rates. Transonic stability is very limited.
- Radical shapes and design features result in bullets that don't match any standard drag curves well, so BC's are highly velocity dependent making trajectory predictions difficult.
- More wetted area and drive bands add to the drag of the bullets, which often results in overestimated performance.
- Longer bullets take up more internal case capacity when seated to the same COAL as conventional bullets.

Chapter 19: Ballistic Performance of Rifle Bullets

Prior editions of *Applied Ballistics for Long Range Shooting* included an appendix of bullet data which was based on live fire testing. The data library grew from about 150 bullets in the first edition to 225 in the second edition. At the time of this third edition release, there is well over 400 bullets worth of data. At one page each, the library has simply grown too large for an appendix.

For this reason, the library of experimentally measured test data has been broken off into another book which is titled *Ballistic Performance of Rifle Bullets.* That book is where the bullet data library will be published from now on. As more calibers and bullets are tested and newer lots of existing bullets are re-tested I will continue to print new editions of *Ballistic Performance of Rifle Bullets* with the most up-to-data experimental data. This third edition of *Applied Ballistics for Long Range Shooting* contains only the basic metrics (SD's, BC's and G7 form factor) for the 533 bullets contained in the 2nd edition of *Ballistic Performance of Rifle Bullets* published in 2015.

Ballistic Performance of Rifle Bullets is a direct product of the Applied Ballistics Laboratory which conducts ongoing live-fire testing in support of ballistic research. In addition to the text book, the bullet data is also made available directly thru the Applied Ballistics Mobile apps for smart phones, Applied Ballistics Kestrels, and other electronics and electro-optics with integrated ballistic software. When you're using one of these ballistic software tools, you're drawing on a pool of data that is supported directly by the ongoing live fire testing done at the lab. New editions of the bullet data text book may only be available every other year, but the software can be updated with the latest library additions many times a year, often within a day of the testing being conducted.

It's very satisfying to see the bullet data used in so many capacities, both static print and directly driving ballistic solutions for so many desktop and field tools. All ballistics calculations are limited by the accuracy of their inputs and those inputs related to the bullets are highly important and often difficult to know. The massive library of live fire data that's being compiled is addressing this issue and allowing for more successful long range shooting.

The following sections show how the bullet data is presented in *Ballistic Performance of Rifle Bullets* and there are several pages of sample data for some of the more popular and interesting bullets.

What is available in *Ballistic Performance of Rifle Bullets*

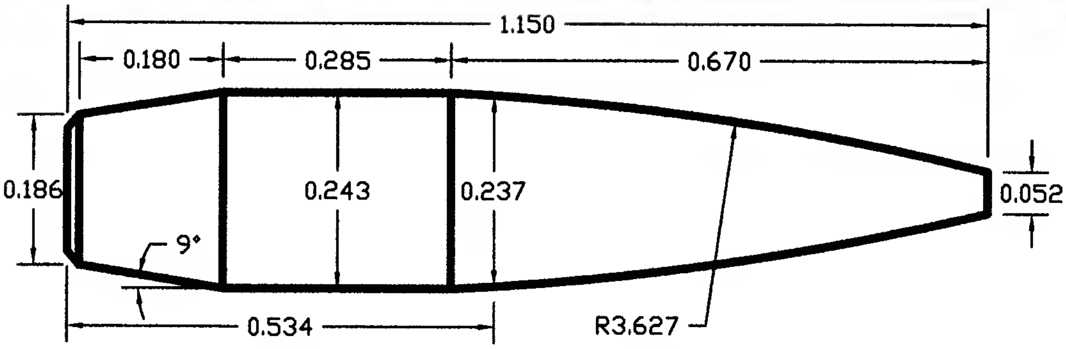
There are two basic uses for the bullet data. One is to compare the various bullets available for your rifle and *select* the best option for your rifle and application. Then, once you've selected a bullet, you can use the detailed data to support highly accurate long range trajectory modeling.

Of course there are other applications such as; using the dimensioned bullet drawings to help with custom chamber reamer designs, comparing stability requirements of different bullets, and gaining insight about the velocity dependence of G1 vs. G7 referenced BC's, along with many other tid-bits.

The following sections will explain where the information comes from on the bullet data pages, how accurate it is, and why it's important.

Ballistic Performance of Rifle Bullets is broken into sections based on caliber, and each caliber is blocked off by brand. There is one full page of data per bullet, starting with a dimensioned drawing and geometric data.

Berger .243 caliber 95 grain VLD



Lot#:	**556**	**Ogive Radius:**	**14.9 calibers**
Sectional Density:	**0.230 lb/in^2**	**Rt/R:**	**0.66**

Figure 19.1. Each data page includes a detailed dimensioned drawing of the bullet.

The dimensioned drawings are useful for many purposes including:

- If you're considering a bullet for hand loading and are interested to see how it needs to be seated to feed from your rifles magazine. In other words, will the bullet nose go down into the case neck when the bullet is seated to magazine length?

- You can use the drawings to assist in custom chamber design for a particular bullet.
- The drawings show you how aggressive the ogive (nose) radius is, which is an indication for how sensitive a bullets' precision might be to seating depth.
- Anyone interested in doing aerodynamic or mass properties modeling of bullets will find the dimensions useful.

The bullets linear dimensions are measured with standard calipers. The overall length is a very accurate measurement, but bullets can typically vary by +/-0.010" in a given lot, more or less depending on the nature of the tip. Open tip, or hollow point bullets tend to have greater variation in length due to the ragged tip compared to Full Metal Jackets or plastic tipped bullets. Of course lot variation can result in length variation as well.

The meplat, or tip diameter is difficult to measure since you're measuring a ragged tip or radius, and as with length, the dimension can vary from bullet to bullet. For both length and meplat diameter, several bullets are measured, and a 'typical' bullet is chosen for full dimensioning. Note that the meplat diameter is the dimension most likely to vary between lots of bullets.

The Boat Tail angle and ogive radius have been measured in various ways, from mounting the bullet in a mini-lathe and collecting points with a dial indicator, to using a Forester datum dial comparator to measure the length to various diameters. Boat tail angle is easily calculated from two points, whereas the nose radius requires at least 3 points to be measured along the curve. Measurements of boat tail angle are good within +/- 0.5 degrees. Ogive radius dimensions are typically repeatable within +/-0.15 calibers, but I've not checked these measurements against many other reliable sources to really know how accurate they are. When dimensioned drawings are available from other sources, my measurements of ogive radius tends to be close.

You'll note on each bullet drawing that the groove diameter is dimensioned across the bearing surface (in Figure 19.1 its 0.243"). You can also see the point on the nose that's equal to the common *bore* diameter for that caliber is indicated as well (in Figure 19.1 it's 0.237").

This dimension is a useful reference for those designing a custom chamber reamer, or considering how a bullet might seat in a known chamber throat. Note that these dimensions are subject to measurement uncertainty, and are based on the particular lot of bullets measured. Lot variation and measurement uncertainty can result in the actual dimensions being somewhat different, so use these dimensions as a guide, with the knowledge they may not be exact for the latest lots of bullets. Also note that bullet comparators vary, and they may not be indicating the actual bore diameter where they encounter the bullet nose.

The information in the blocks below the bullet drawing is just a few metrics which further characterize the bullets geometry. The lot number is given for bullets where it's known, otherwise it's simply listed as *unknown.*

The bullets sectional density is shown, which characterizes the bullets ability to penetrate targets, as well as air. The relationship between Sectional Density and Ballistic coefficient is explained in Chapter 2 of this book.

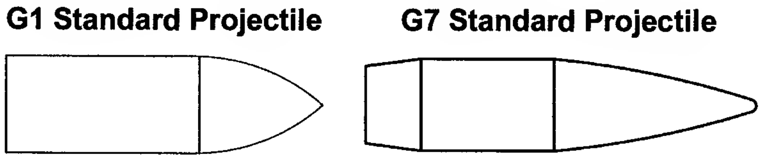
The bullets ogive radius in calibers is also given. This is simply the ogive radius in inches, divided by the caliber of the bullet. So for example, the bullet in Figure 19.1 has an ogive radius of 3.627", and a caliber of 0.243". So the ogive radius is 3.627" divided by 0.243" equals 14.9 calibers.

Bullet noses are typically sections of circular arcs. Circles are defined by the length of their radius, and that's all we're talking about here. Bullets having a long radius for their caliber will typically have lower drag.

Finally, the Rt/R ratio is shown. This is a measure of how tangent or secant a nose is. Rt/R ratios close to 1.0 will have a very smooth connection between the nose curvature and the bearing surface. This type of nose geometry is known as tangent. Bullets that have a very abrupt connection between the nose and bearing surface are known as secant (or VLD) and will have Rt/R ratios closer to 0.5.

Tangent bullets having Rt/R ratios close to 1.0 are known for easy precision, meaning they tend to be less sensitive to how they're loaded for different rifles. The downside of the tangent ogive design is that they're higher drag than a secant nose.

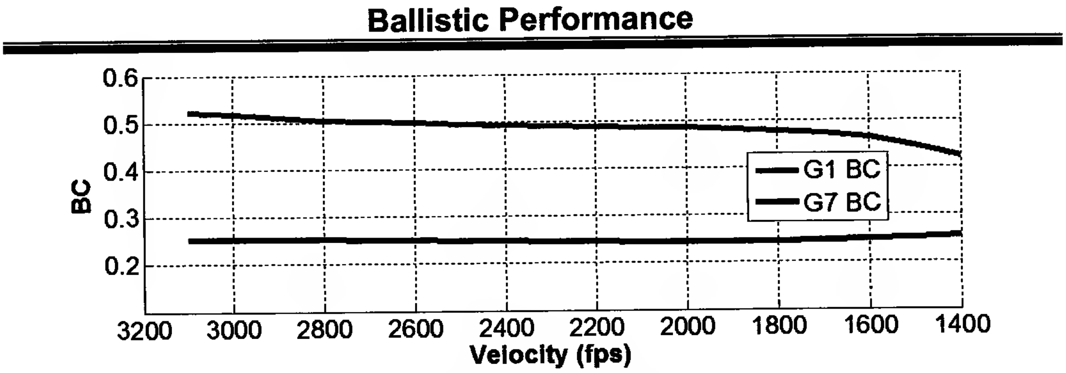
A secant nose, or a bullet with an Rt/R ratio closer to 0.5 (think VLD nose) has the advantage of lower drag, but are known for being more sensitive to seating depth. In summary: an Rt/R close to 1.0 means easy accuracy, but not necessarily high BC, whereas Rt/R ratios closer to 0.5 means finicky accuracy but high BC. The Berger Hybrid nose design is a combination of a Tangent ogive at the bearing surface juncture which transitions to a Secant ogive at some point on the nose forward of where the riflings contact the bullet. This configuration allows for the best of both worlds, in terms of easy precision and drag reduction.



G1 Standard Projectile **G7 Standard Projectile**

Figure 19.2. G1 and G7 standard projectiles

The next section of the bullet data pages presents the bullets external ballistic performance in terms of G1 and G7 BC's. Chapter 2 goes into this in detail. Here, I'll just say that the G1 standard was established in the industry many years ago when bullets looked more like that (flat based blunt nosed on the left side of Figure 19.2). With modern bullets having evolved with longer noses and boat tails, the G7 standard is now more appropriate because the G7 BC better represents the drag of modern bullets over greater ranges than the G1 model.



	Above 3000	3000-2500	2500-2000	2000-1500	Below 1500
G1 BC	0.533	0.506	0.490	0.465	0.445
G7 BC	0.252	0.251	0.246	0.247	0.251

Averages from 3000 fps to 1500 fps:
G1 BC: 0.485, variation of G1 BC: 0.071
G7 BC: 0.249, variation of G7 BC: 0.009
G7 form factor: 0.923

Figure 19.3. Ballistic Performance data.

The ballistic performance data shows a plot of G1 and G7 BC over a typical range of velocities from muzzle to long range. For modern long range bullets, you'll typically see more variation in the G1 BC than the G7 BC. ***This speed dependent variation of the G1 BC leads to inaccurate trajectory predictions and prevents valid apples-to-apples comparisons of bullet performance.***

For most bullets which have more variation in the G1 BC, the G1 data is shown in gray to indicate that it's a poor fit for that bullet. The G7 data is shown in black to indicate that it's a better fit. In rare cases when the G1 drag model is a better fit, that data is shown in black and the G7 will be gray. This is only true for several bullets which tend to have wide tips and shallow or no boat tail.

Below the BC graph is a table which shows what the G1 and G7 BC's are in velocity bands. This is just a numeric representation of the data shown in the plot, which can be entered into a ballistics program that takes segmented BC's. Again, gray numbers are a bad fit, and shouldn't be used.

Below the velocity segmented table, the performance is boiled down into single number averages. For those looking for that ‘one number’ they can use to model or compare bullet performance, this is it. All BC’s are averaged over a common speed range of 3000 fps to 1500 fps. **The most important number on the page, the best fitting BC average, is bold and highlighted.** In the example shown in Figure 19.3, the best fitting model is G7, and the G7 BC is 0.249.

The G7 form factor is a measure of drag for the bullet compared to the G7 standard. A bullet with a form factor of 1.00 means that bullet has the same drag as the G7 standard projectile (shown in Figure 19.2 above). If a bullets’ form factor is less than 1.00, then it has less drag than the G7 standard, vice versa for a form factor greater than 1.00.

Typically, form factors vary from 0.80 for the most streamlined shapes, to 1.20+ for short nose, blunt, flat based bullets. For good long range performance, you want to look for form factors in the low 0.90’s or lower.

BC is actually just sectional density divided by form factor, so for example, the bullet used in this example is a 95 grain .243 caliber bullet, so its SD is 0.230. The G7 form factor is 0.923, so it’s G7 BC is 0.230/0.923 = 0.249.

The final block of data relates to the bullet stability requirements. Stability can be tricky because it’s highly dependent on environmental conditions and velocity. A bullet fired from a rifle might be perfectly stable at 5000 feet altitude (where the air is relatively thin), but if you fire it down at sea level where the air is thicker, it will be less stable and may tumble.

Rifling Twist Rate and Stability

		Stability Factor	
Barrel Twist	**Best case**	**Nominal**	**Worst Case**
1:7"	2.47	2.16	1.87
1:8"	1.89	1.66	1.43
1:9"	1.50	1.31	1.13
1:10"	1.21	1.06	0.92

Minimum twist required for stability is 1:8.8"

Recommended twist for optimal performance is 1:7.9" or faster

Figure 19.4. Rifling twist rate and stability.

The stability table is sort of mapping out the range of stability scenarios for you so you can make well informed decisions about barrel twist for a given bullet. The conditions which define Best, Nominal and Worst case stability scenarios are as follows:

- Best case: 1000 feet altitude, 100% humidity, 100 degrees F, and 3000 fps muzzle velocity.

- Nominal case: sea level, 50% humidity, 59 degrees F, and 2800 fps muzzle velocity.
- Worse case: sea level, 0% humidity, 0 degrees F, and 2600 fps muzzle velocity.

The numbers shown in the table as 'Stability Factor' is referring to the gyroscopic stability factor which defines how stable a bullet is. Mathematically, anything above 1.0 is defined as 'stable'. However in practice, due to error in the calculations, variations in velocity and atmospherics, you want your bullets to have a stability factor somewhat greater than 1.0. In general, a stability factor of 1.2 will get the bullets to fly straight and accurate, but may be flying with some wobble, which can reduce the effective BC. Plus, if your stability is marginal in one condition, it may be inadequate for a slightly different condition.

A stability factor of 1.5 or higher is recommended to fully stabilize a bullet and get its full BC potential[30].

Finally, below the table of stability values is a summary which suggests a minimum and recommended twist rate to achieve certain stability conditions.

The 'Minimum twist required for stability' is based on achieving a stability factor of 1.2 in standard sea level conditions[31] and 2800 fps muzzle velocity. The 'Recommended twist for optimal performance' is based on achieving a stability factor of 1.5 in the same conditions.

Remember that if you're considering a bullet for use in a rifle which has a twist rate slower than recommended, it may work just fine if you're shooting in a favorable (low air density) environment. This is why the table is shown with the best, nominal, and worst case scenarios; so you can determine stability in various conditions. The 'Minimum' and 'Recommended' barrel twists are just boiled down numbers which are conservative guidelines.

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[30] There are several chapters in *Modern Advancements in Long Range Shooting-Volume 1* which discuss the relationship between Stability and BC.

[31] 29.92 inHg, 59 degrees F, and 0% Humidity.

References

1. Robert L. McCoy, *"Modern Exterior Ballistics"*, 1999 Schiffer Publishing, LTD

2. Harold R. Vaughn, *"Rifle Accuracy Facts"*, 2000 Precision Shooting, Inc.

3. Donald E. Carlucci & Sidney S. Jacobson, *"Ballistics, Theory and Design of Guns and Ammunition"*, CRC Press 2008

4. Franklin Weston Mann, *"The Bullet's Flight From Powder to Target: The Internal and External Ballistics of Small Arms"*, New York Munn & Co, Publishers 1909

5. George Klimi, *"Exterior Ballistics: A New Approach"*, Xlibris Corporation

6. John Barsness, Craig Boddington, John Haviland, Richard Mann, Ron Spomer, Bryce Towsley, *"Rifle Bullets for the Hunter"*, Ballistic Technology

7. David C. Wilcox, *"Basic Fluid Mechanics"*, DCW Industries

8. John D. Anderson, *"Modern Compressible Flow"*, McGraw-Hill, Inc.

9. John D. Nicolaides, *"Missile Flight and Astrodynamics"*, Bureau of Weapons, Department of the Navy, Washington D.C.

10. Bryan Litz, *"Modern Advancements in Long Range Shooting – Volume 1"* Applied Ballistics LLC, Cedar Springs, MI.

11. Bryan Litz, *"Accuracy and Precision for Long Range Shooting"*, Applied Ballistics LLC, Cedar Springs, MI.

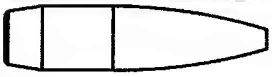
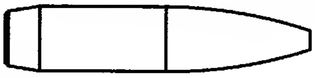
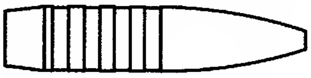
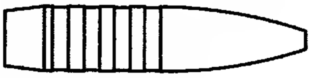
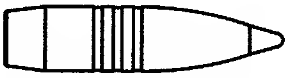
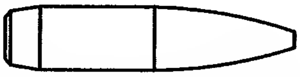
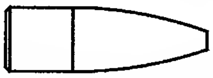
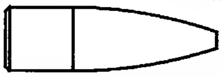
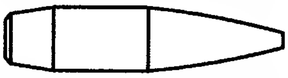
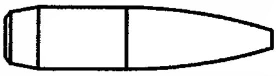
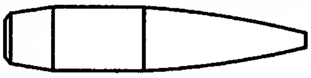
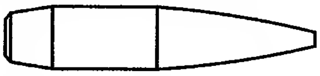
Appendix A

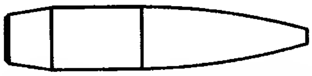
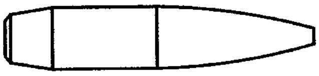
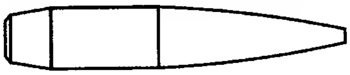
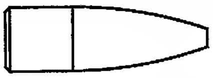
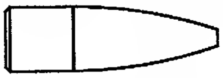
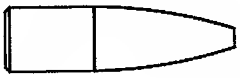
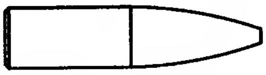
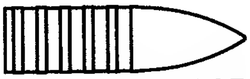
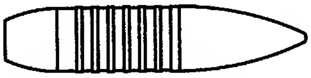
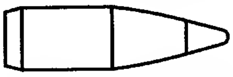
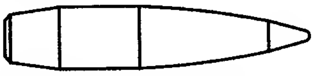
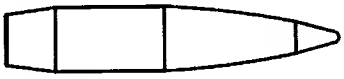
This Appendix tabulates the basic live fire test data for the 533 bullet library which was published in the 2nd edition of *Ballistic Performance of Rifle Bullets* in 2015. Only the following basic information is tabulated here for each bullet:

- Sectional Density: SD
- G7 form factor: i_7
- Average G7 BC from 3000 to 1500 fps
- Average G1 BC from 3000 to 1500 fps

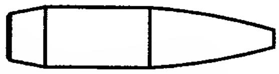
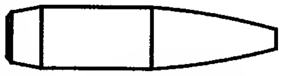
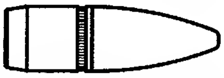
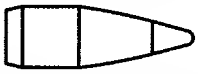
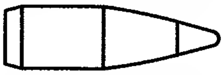
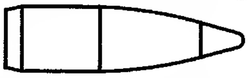
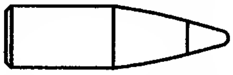
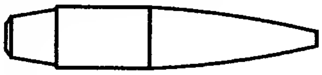
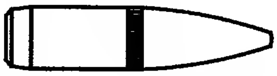
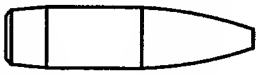
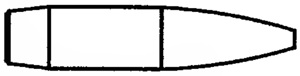
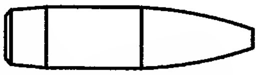
For more details of each bullet including: 2-D drawing, velocity banded BC's, and stability information, refer to *Ballistic Performance of Rifle Bullets.*

.224 Caliber bullets

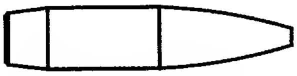
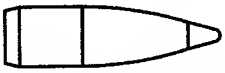
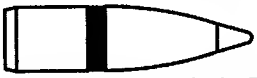
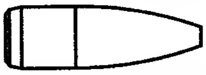
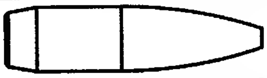
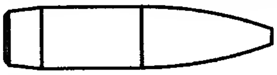
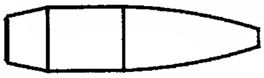
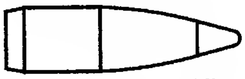
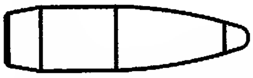
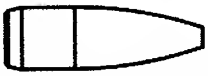
Bullet	SD	i_7	G7 BC	G1 BC
 Barnes 69 Match Burner	0.197	1.172	0.168	0.326
 Barnes 85 Match Burner	0.242	1.188	0.204	0.397
 Barnes 70 TacX MIL/LE	0.199	1.295	0.154	0.300
 Barnes 70 TSXBT	0.199	1.260	0.158	0.308
 Barnes 62 TTSXBT	0.177	1.243	0.142	0.277
 Berger 77 Tactical OTM	0.219	1.142	0.192	0.374
 Berger 52 Target FB	0.148	1.231	0.120	0.234
 Berger 55 Target FB	0.157	1.205	0.130	0.253
 Berger 70 Target VLD	0.199	1.042	0.191	0.373
 Berger 73 Target Boat Tail	0.208	1.168	0.178	0.347
 Berger 75 Target VLD	0.214	0.989	0.216	0.421
 Berger 80 Target VLD	0.228	0.977	0.233	0.455

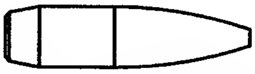
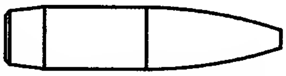
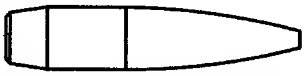
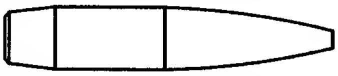
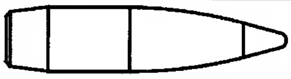
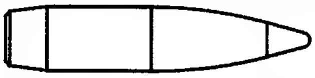
	(.224 Caliber bullets continued)			
Bullet	**SD**	**i_7**	**G7 BC**	**G1 BC**
 *Berger 80.5 Target FULLBORE*	0.229	1.015	0.277	0.443
 *Berger 82 Target Boat Tail*	0.233	1.038	0.225	0.438
 *Berger 90 Target VLD*	0.256	0.937	0.273	0.533
 *Berger 52 Varmint FB*	0.148	1.437	0.103	0.201
 *Berger 55 Varmint FB*	0.157	1.463	0.107	0.209
 *Berger 60 Varmint FB*	0.171	1.229	0.139	0.271
 *DRT 79 Frangible*	0.225	1.182	0.190	0.371
 *GS Custom 57 SP*	0.162	1.639	0.099	0.193
 *GS Custom 69 SP*	0.197	1.373	0.143	0.279
 *Hornady 52 Amax*	0.148	1.240	0.120	0.234
 *Hornady 75 Amax*	0.214	0.997	0.214	0.418
 *Hornady 80 Amax*	0.228	0.987	0.231	0.450

(.224 Caliber bullets continued)

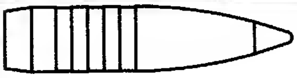
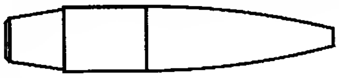
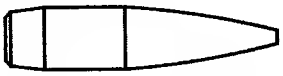
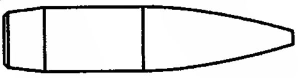
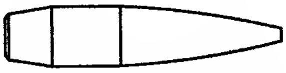
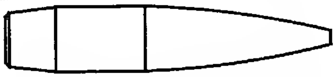
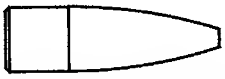
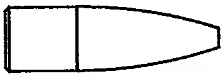
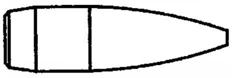
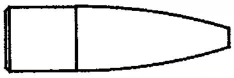
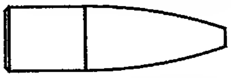
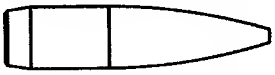
Bullet	**SD**	**i_7**	**G7 BC**	**G1 BC**
 *Hornady 68 BTHP*	0.194	1.107	0.175	0.341
 *Hornady 75 BTHP*	0.214	1.170	0.183	0.356
 *Hornady 55 FMJBT*	0.157	1.264	0.124	0.241
 *Hornady 40 Vmax*	0.114	1.308	0.087	0.170
 *Hornady 50 Vmax*	0.142	1.293	0.110	0.216
 *Hornady 53 Vmax*	0.151	1.161	0.130	0.254
 *Hornady 55 Vmax*	0.157	1.284	0.122	0.238
 *JLK 80 VLD*	0.228	0.989	0.230	0.449
 *Lake City 62 FMJBT*	0.177	1.148	0.154	0.300
 *Lapua 69 Scenar*	0.197	1.164	0.169	0.329
 *Lapua 77 Scenar*	0.219	1.063	0.206	0.401
 *Lapua 69 Scenar L*	0.197	1.098	0.179	0.348

(.224 Caliber bullets continued)

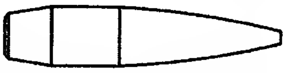
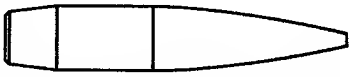
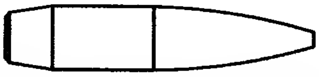
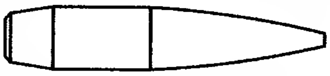
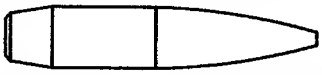
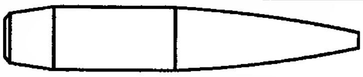
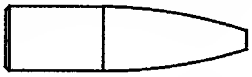
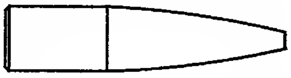
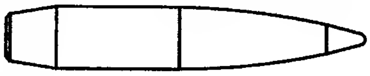
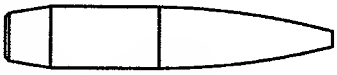
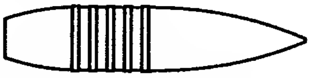
Bullet	SD	i_7	G7 BC	G1 BC
 *Lapua 77 Scenar L*	0.219	1.082	0.203	0.394
 *Nosler 55 Ballistic Tip*	0.157	1.205	0.130	0.254
 *Nosler 60 Ballistic Tip*	0.171	1.288	0.133	0.259
 *Nosler 52 Custom Competition*	0.148	1.311	0.113	0.220
 *Nosler 69 Custom Competition*	0.197	1.239	0.159	0.309
 *Nosler 77 Custom Competition*	0.219	1.138	0.193	0.375
PMC 62 FMJBT Green Tip Ammo	0.177	1.096	0.161	0.314
 *RUAG 69 Swiss P Target*	0.197	1.191	0.165	0.322
 *Sierra 55 BlitzKing*	0.157	1.214	0.129	0.252
Sierra 55 FMJ	0.157	1.194	0.131	0.255
 *Sierra 65 GameKing*	0.185	1.217	0.152	0.296
 *Sierra 52 MatchKing*	0.148	1.328	0.112	0.217

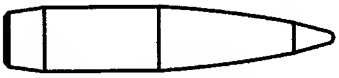
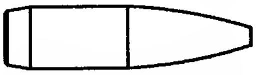
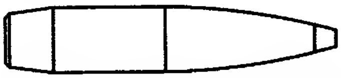
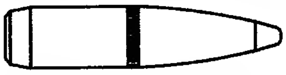
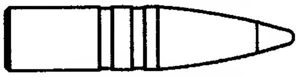
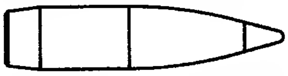
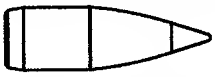
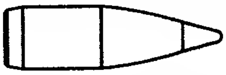
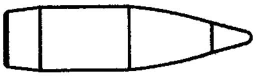
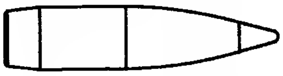
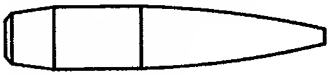
(.224 Caliber bullets continued)				
Bullet	**SD**	**i_7**	**G7 BC**	**G1 BC**
 *Sierra 69 MatchKing*	0.197	1.161	0.169	0.330
 *Sierra 77 MatchKing*	0.219	1.135	0.193	0.376
 *Sierra 80 MatchKing*	0.228	1.030	0.221	0.431
 *Sierra 90 MatchKing*	0.256	0.999	0.257	0.499
 *Sierra 69 Tipped MatchKing*	0.197	1.082	0.182	0.354
 *Sierra 77 Tipped MatchKing*	0.219	1.085	0.202	0.394

.243 Caliber (6mm) bullets

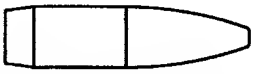
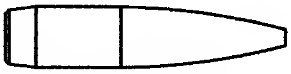
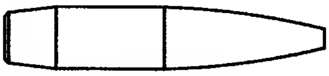
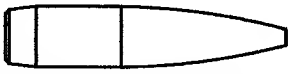
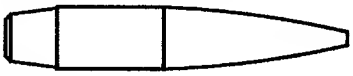
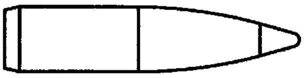
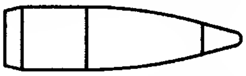
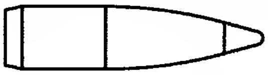
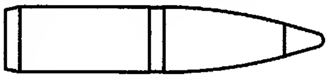
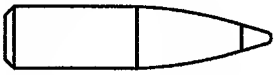
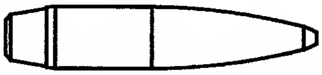
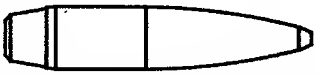
Bullet	SD	i7	G7 BC	G1 BC
 *Barnes 80 TTSXBT*	0.194	1.214	0.159	0.311
 *Barts 105 RBT*	0.254	0.988	0.257	0.501
 *Berger 87 Hunting VLD*	0.211	0.961	0.219	0.427
 *Berger 95 Classic Hunter*	0.230	1.033	0.223	0.434
 *Berger 95 Hunting VLD*	0.230	0.962	0.239	0.465
 *Berger 105 Hunting VLD*	0.254	0.915	0.278	0.541
 *Berger 62 Target EUWIN*	0.150	1.293	0.116	0.226
 *Berger 64.25 Target Column*	0.155	1.318	0.118	0.229
 *Berger 65 Target BT*	0.246	1.248	0.126	0.245
 *Berger 65 Target WEB BR*	0.246	1.248	0.126	0.245
 *Berger 68 Target FB*	0.165	1.256	0.131	0.255
 *Berger 90 Target BT*	0.218	1.037	0.210	0.409

(6mm bullets continued)

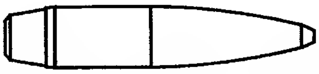
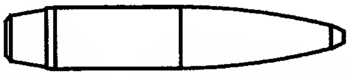
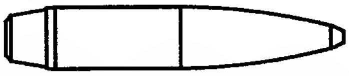
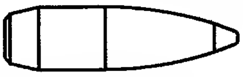
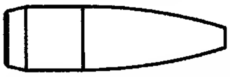
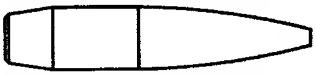
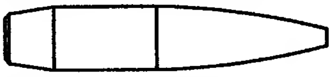
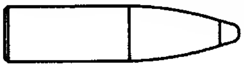
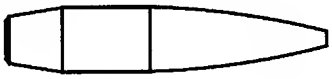
Bullet	SD	i_7	G7 BC	G1 BC
 *Berger 95 Target VLD*	0.230	0.958	0.240	0.467
 *Berger 105 Target Hybrid*	0.254	0.925	0.275	0.535
 *Berger 105 Target Boat Tail*	0.254	1.004	0.253	0.493
 *Berger 105 Target VLD*	0.254	0.961	0.265	0.515
 *Berger 108 Target Boat Tail*	0.261	0.997	0.268	0.521
 *Berger 115 Target VLD*	0.278	0.963	0.289	0.563
Berger 69 Varmint High BC FB	0.167	1.128	0.148	0.288
 *Berger 80 Varmint FB*	0.194	1.257	0.154	0.300
 *Berger 88 Varmint HBC FB*	0.213	1.092	0.195	0.380
 *DTAC 117 BT*	0.283	1.000	0.283	0.553
 *DTAC 115 BTHP*	0.278	1.007	0.276	0.538
 *GS Custom 81 SP*	0.196	1.195	0.164	0.320

(6mm bullets continued)				
Bullet	**SD**	**i_7**	**G7 BC**	**G1 BC**
 GS Custom 109 SP	0.264	1.054	0.251	0.490
 *Hornady 105 Amax*	0.254	1.010	0.252	0.491
 *Hornady 87 BTHP*	0.211	1.181	0.178	0.347
 *Hornady 105 BTHP Match*	0.254	1.032	0.246	0.479
 *Hornady 100 BTSP*	0.242	1.225	0.198	0.385
 *Hornady 80 GMX*	0.194	1.347	0.144	0.280
 *Hornady 85 Interbond*	0.206	1.081	0.190	0.371
 *Hornady 58 Vmax*	0.140	1.177	0.119	0.233
 *Hornady 65 Vmax*	0.157	1.178	0.134	0.261
 *Hornady 75 Vmax*	0.182	1.115	0.163	0.317
 *Hornady 87 Vmax*	0.211	1.076	0.196	0.381
 *JLK 105 VLD*	0.254	0.950	0.267	0.521

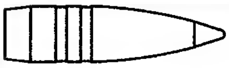
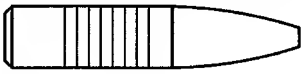
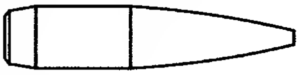
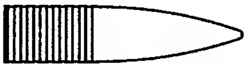
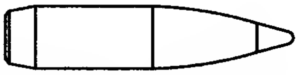
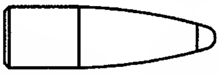
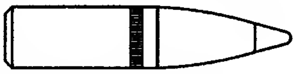
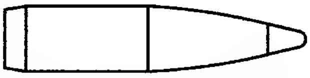
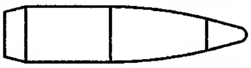
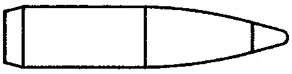
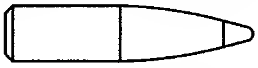
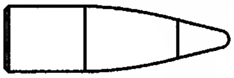
(6mm bullets continued)

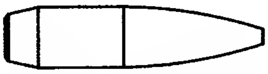
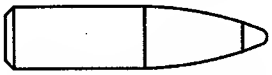
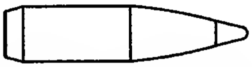
Bullet	SD	i_7	G7 BC	G1 BC
 *Lapua 90 FMJBT*	0.218	1.180	0.185	0.360
 *Lapua 90 Scenar*	0.218	0.999	0.218	0.424
 *Lapua 105 Scenar*	0.254	1.025	0.248	0.483
 *Lapua 90 Scenar L*	0.218	1.031	0.211	0.411
 *Matrix 107 VLD*	0.259	0.982	0.264	0.513
 *Nosler 90 Accubond*	0.218	1.198	0.182	0.355
 *Nosler 70 Ballistic Tip*	0.169	1.184	0.143	0.280
 *Nosler 80 Ballistic Tip*	0.194	1.172	0.165	0.323
 *Nosler 90 E-Tip*	0.218	1.328	0.164	0.320
 *Nosler 95 Partition*	0.230	1.303	0.177	0.343
 *Precision Ballistics 103 VLD*	0.249	1.067	0.234	0.456
 *Precision Ballistics 105 VLD*	0.254	1.058	0.240	0.469

(6mm bullets continued)

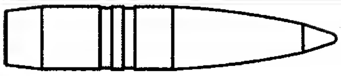
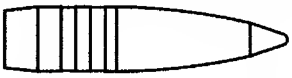
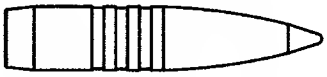
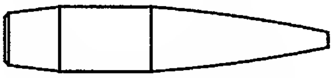
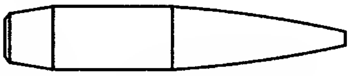
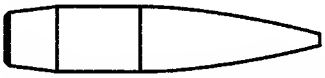
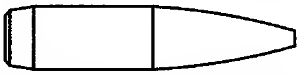
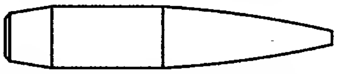
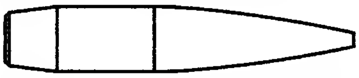
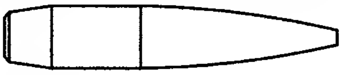
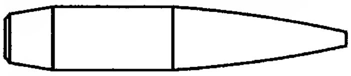
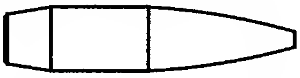
Bullet	SD	i_7	G7 BC	G1 BC
 *Precision Ballistics 108 VLD*	0.261	1.037	0.252	0.492
 *Precision Ballistics 113 VLD*	0.274	1.070	0.256	0.499
 *Precision Ballistics 115 VLD*	0.278	1.096	0.254	0.495
 *Sierra 80 Blitz*	0.194	1.256	0.154	0.300
 *Sierra 70 MatchKing*	0.169	1.286	0.132	0.257
 *Sierra 95 MatchKing*	0.230	0.993	0.231	0.451
 *Sierra 107 MatchKing*	0.259	0.994	0.260	0.507
 *Sierra 100 ProHunter*	0.242	1.323	0.183	0.356
 *Vapor Trail 103 BTHP*	0.249	0.958	0.260	0.507

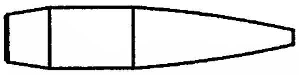
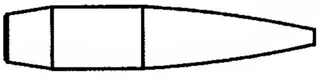
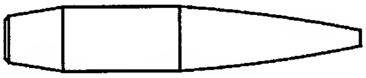
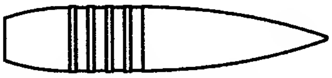
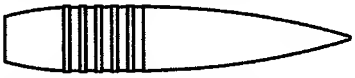
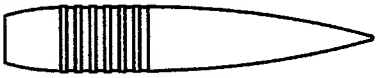
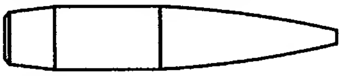
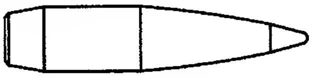
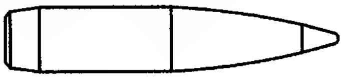
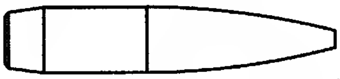
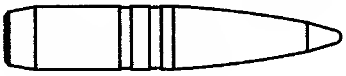
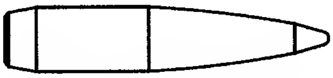
25 Caliber (.257”) bullets

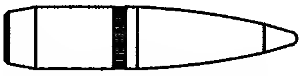
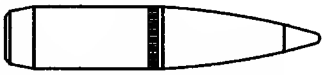
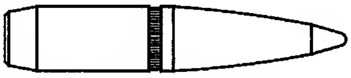
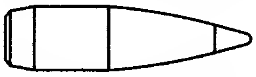
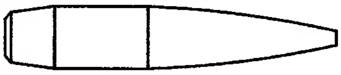
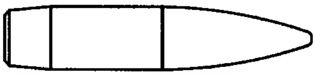
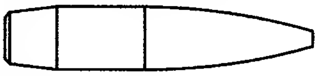
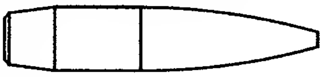
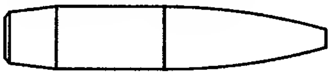
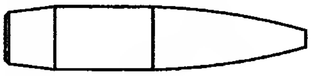
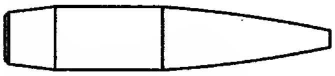
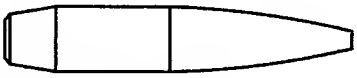
Bullet	SD	i_7	G7 BC	G1 BC
 *Barnes 80 TTSXBT*	0.173	1.184	0.146	0.285
 *Barnes 115 TSX FB*	0.249	1.481	0.168	0.327
 *Berger 115 VLD*	0.249	1.006	0.247	0.482
 *GS Custom 90 SP*	0.195	1.240	0.157	0.307
 *Hornady 110 Interbond*	0.238	1.169	0.204	0.398
 *Hornady 87 Spitzer*	0.188	1.298	0.145	0.282
 *Hornady 117 SST*	0.253	1.298	0.195	0.380
 *Nosler 110 Accubond*	0.238	1.166	0.204	0.399
 *Nosler 100 Ballistic Tip*	0.216	1.227	0.176	0.345
 *Nosler 115 Ballistic Tip*	0.249	1.219	0.204	0.399
 *Nosler 115 Partition*	0.249	1.257	0.198	0.386
 *Sierra 70 BlitzKing*	0.151	1.296	0.117	0.228

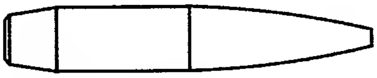
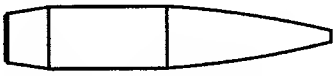
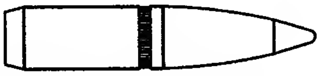
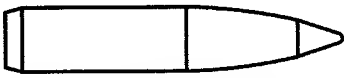
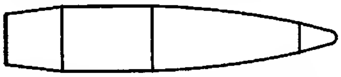
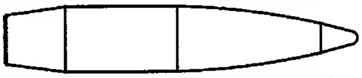
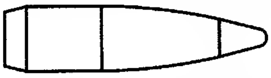
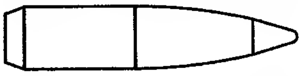
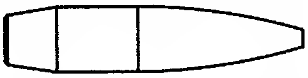
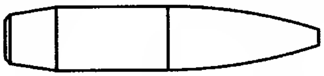
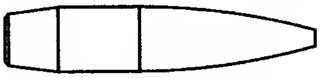
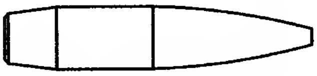
(257 caliber bullets continued)				
Bullet	**SD**	i_7	**G7 BC**	**G1 BC**
 *Sierra 100 MatchKing*	0.216	1.173	0.184	0.360
 *Sierra 117 ProHunter*	0.253	1.410	0.180	0.349
 *Swift 100 Scirocco II*	0.216	1.249	0.174	0.340

.264 Caliber (6.5mm) bullets

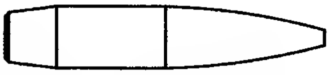
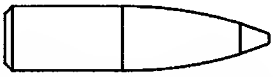
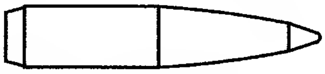
Bullet	SD	i_7	G7 BC	G1 BC
 *Barnes 127 LRXBT*	0.260	1.141	0.228	0.446
 *Barnes 100 TTSXBT*	0.205	1.172	0.175	0.341
 *Barnes 120 TTSXBT*	0.246	1.212	0.203	0.396
 *Berger 130 Hunting VLD*	0.266	0.926	0.288	0.561
 *Berger 140 Hunting VLD*	0.287	0.935	0.307	0.598
 *Berger 130 Tactical AR Hybrid*	0.267	0.929	0.287	0.559
 *Berger 120 Target BT*	0.246	1.025	0.240	0.468
 *Berger 130 Target VLD*	0.267	0.927	0.288	0.560
 *Berger 140 Target Hybrid*	0.287	0.923	0.311	0.606
 *Berger 140 Target LR BT*	0.287	0.944	0.304	0.592
 *Berger 140 Target VLD*	0.287	0.945	0.304	0.591
 *Cauterucio 119 10-ogive*	0.244	1.012	0.241	0.470

(6.5mm bullets continued)				
Bullet	**SD**	**i_7**	**G7 BC**	**G1 BC**
 *Cauterucio 119 15-ogive*	0.244	0.916	0.266	0.519
 *Cauterucio 131 VLD*	0.269	0.907	0.296	0.577
 *Cauterucio 155 VLD*	0.318	0.946	0.336	0.654
 *GS Custom 112 SP*	0.230	1.219	0.189	0.368
 *GS Custom 119 SP*	0.244	1.145	0.213	0.417
 *GS Custom 128 SP*	0.262	1.056	0.249	0.487
 *Hoover 136*	0.279	0.888	0.314	0.612
 *Hornady 123 Amax*	0.252	1.055	0.239	0.467
 *Hornady 140 Amax*	0.287	0.996	0.288	0.562
 *Hornady 140 BTHP Match*	0.287	1.008	0.285	0.554
 *Hornady 120 GMX*	0.246	1.089	0.226	0.442
 *Hornady 129 Interbond*	0.264	0.999	0.265	0.518

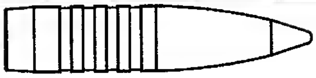
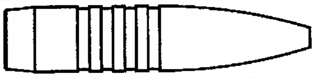
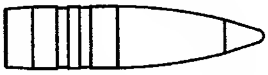
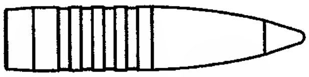
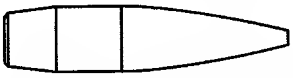
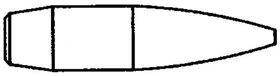
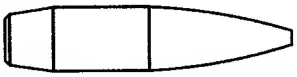
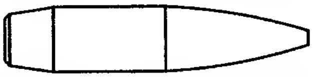
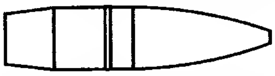
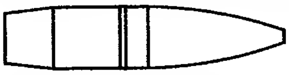
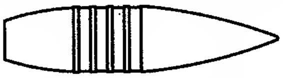
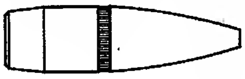
(6.5mm bullets continued)				
Bullet	**SD**	**i_7**	**G7 BC**	**G1 BC**
 *Hornady 123 SST BT*	0.252	1.069	0.236	0.462
 *Hornady 129 SST BT*	0.264	1.072	0.247	0.482
 *Hornady 140 SST BT*	0.287	1.085	0.265	0.517
 *Hornady 95 Vmax*	0.195	1.069	0.182	0.356
 *JLK 140 VLD*	0.287	0.895	0.321	0.625
 *Lapua 144 FMJBT*	0.295	1.023	0.289	0.562
 *Lapua 108 Scenar*	0.221	0.985	0.225	0.438
 *Lapua 123 Scenar*	0.252	0.950	0.265	0.517
 *Lapua 139 Scenar*	0.285	0.983	0.290	0.564
 *Lapua 120 Scenar L*	0.246	1.018	0.242	0.470
 *Lapua 136 Scenar L*	0.279	0.969	0.288	0.560
 *Matrix 150 BTHP*	0.308	0.992	0.310	0.604

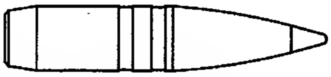
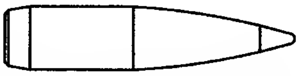
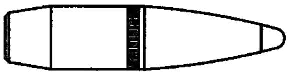
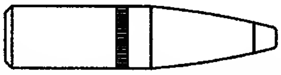
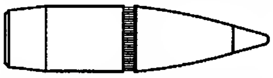
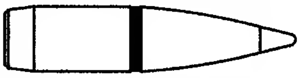
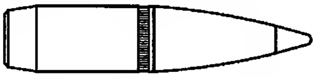
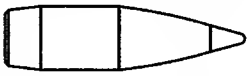
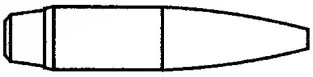
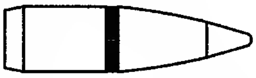
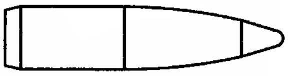
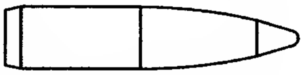
				(6.5mm bullets continued)
Bullet	**SD**	i_7	**G7 BC**	**G1 BC**
 *Matrix 160 BTHP*	0.328	0.989	0.332	0.646
 *Norma 130 Diamond*	0.267	0.905	0.294	0.575
 *Nosler 130 Accubond*	0.267	1.185	0.225	0.440
 *Nosler 140 Accubond*	0.287	1.214	0.237	0.463
 *Nosler 129 LR Accubond*	0.264	0.935	0.283	0.552
 *Nosler 142 LR Accubond*	0.291	0.993	0.293	0.572
 *Nosler 100 Ballistic Tip*	0.205	1.193	0.172	0.336
 *Nosler 120 Ballistic Tip*	0.246	1.149	0.214	0.419
 *Nosler 123 Custom Competition*	0.252	1.048	0.241	0.468
 *Nosler 140 Custom Competition*	0.287	1.021	0.281	0.547
 *Sierra 107 MatchKing*	0.219	0.954	0.230	0.448
 *Sierra 123 MatchKing*	0.252	0.970	0.260	0.506

(6.5mm bullets continued)

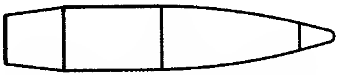
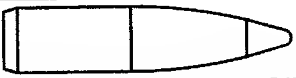
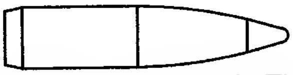
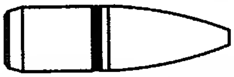
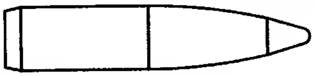
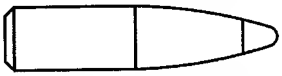
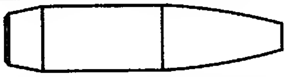
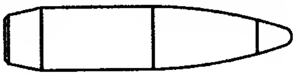
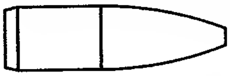
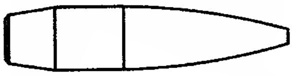
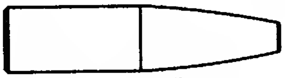
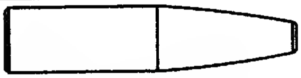
Bullet	**SD**	**i_7**	**G7 BC**	**G1 BC**
 *Sierra 142 MatchKing*	0.291	0.968	0.301	0.585
 *Sierra 120 ProHunter*	0.246	1.207	0.204	0.397
 *Swift 130 Scirocco*	0.267	1.061	0.251	0.491

270 Caliber (.277") bullets

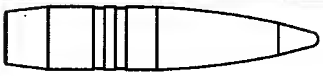
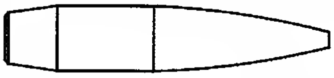
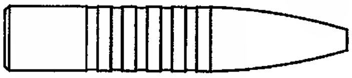
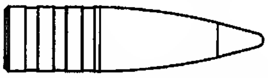
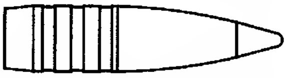
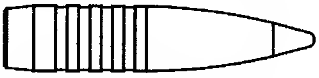
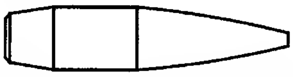
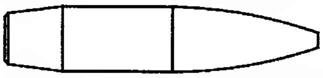
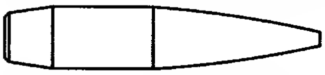
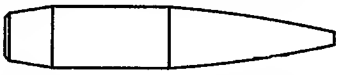
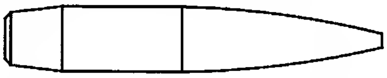
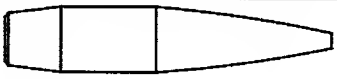
Bullet	SD	i_7	G7 BC	G1 BC
 Barnes 130 TSXBT	0.242	1.248	0.194	0.378
 Barnes 140 TSXBT	0.261	1.272	0.205	0.399
 Barnes 110 TTSXBT	0.205	1.189	0.172	0.336
 Barnes 130 TTSXBT	0.242	1.266	0.191	0.373
 Berger 130 Classic Hunter	0.242	0.961	0.252	0.491
 Berger 130 Hunting VLD	0.242	1.025	0.236	0.460
 Berger 140 Hunting VLD	0.261	1.011	0.258	0.502
 Berger 150 Hunting VLD	0.279	1.054	0.265	0.516
 Cutting Edge 120 HPBT	0.223	1.070	0.209	0.407
 Cutting Edge 130 HPBT	0.242	1.065	0.227	0.443
 GS Custom 105 SP	0.196	1.258	0.156	0.304
 Hornady 110 BTHP	0.205	1.132	0.181	0.352

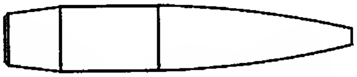
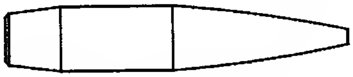
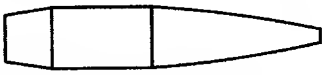
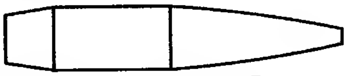
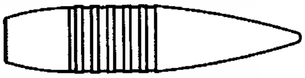
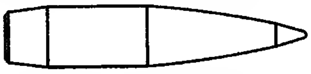
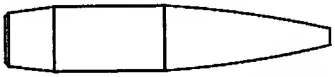
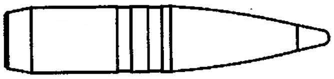
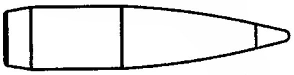
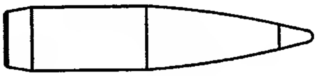
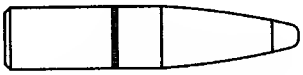
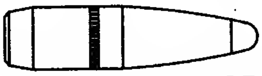
(.270 caliber bullets continued)				
Bullet	**SD**	**i_7**	**G7 BC**	**G1 BC**
 *Hornady 130 GMX*	0.242	1.142	0.212	0.414
 *Hornady 130 Interbond*	0.242	1.059	0.229	0.447
 *Hornady 140 BTSP Interlock*	0.261	1.145	0.228	0.443
 *Hornady 150 SP Interlock*	0.279	1.348	0.207	0.403
 *Hornady 120 SST BT*	0.223	1.176	0.190	0.370
 *Hornady 130 SST BT*	0.242	1.084	0.223	0.436
 *Hornady 140 SST BT*	0.261	1.086	0.240	0.469
 *Hornady 110 Vmax*	0.205	1.138	0.180	0.351
 *Matrix 150 RBT*	0.279	1.211	0.231	0.449
 *Nosler 100 Accubond*	0.186	1.255	0.149	0.290
 *Nosler 130 Accubond*	0.242	1.224	0.198	0.387
 *Nosler 140 Accubond*	0.261	1.200	0.217	0.424

(.270 caliber bullets continued)

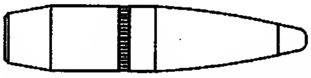
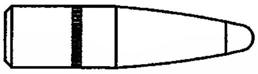
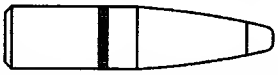
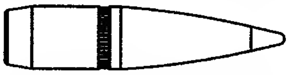
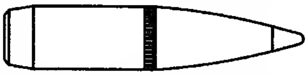
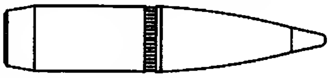
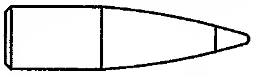
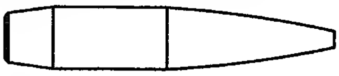
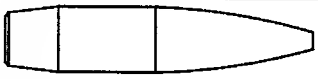
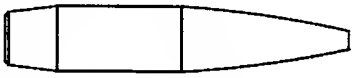
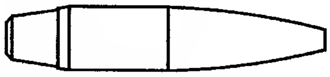
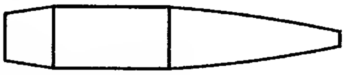
Bullet	SD	i_7	G7 BC	G1 BC
 *Nosler 150 LR Accubond*	0.279	0.959	0.291	0.568
 *Nosler 130 Ballistic Silver Tip*	0.242	1.215	0.199	0.390
 *Nosler 140 Ballistic Tip*	0.261	1.148	0.227	0.444
 *Nosler 115 Custom Competition*	0.214	1.347	0.159	0.311
 *Nosler 130 E-Tip*	0.242	1.258	0.192	0.376
 *Nosler 140 Partition*	0.261	1.257	0.208	0.404
 *Sierra 140 GameKing*	0.261	1.394	0.187	0.364
 *Sierra 150 GameKing*	0.279	1.180	0.237	0.461
 *Sierra 115 MatchKing*	0.214	1.325	0.162	0.315
 *Sierra 135 MatchKing*	0.251	0.992	0.253	0.494
 *Swift 140 A-Frame*	0.261	1.531	0.172	0.332
 *Swift 150 A-Frame*	0.279	1.516	0.186	0.360

.284 Caliber (7mm) bullets

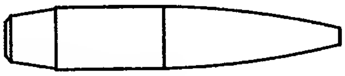
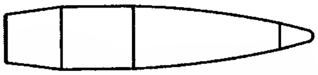
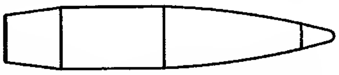
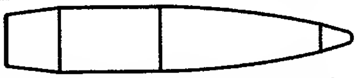
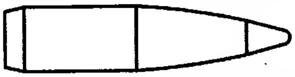
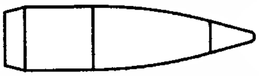
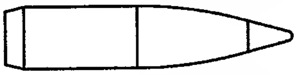
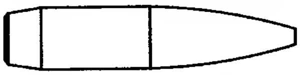
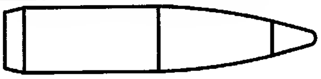
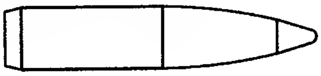
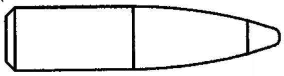
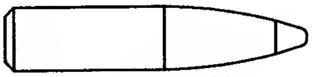
Bullet	SD	i_7	G7 BC	G1 BC
 *Barnes 145 LRXBT*	0.257	1.078	0.238	0.465
 *Barnes 171 Match Burner*	0.303	0.977	0.310	0.604
 *Barnes 175 TSX FB*	0.310	1.497	0.207	0.403
 *Barnes 110 TTSX FB*	0.195	1.257	0.155	0.303
 *Barnes 120 TTSXBT*	0.213	1.138	0.187	0.364
 *Barnes 140 TTSXBT*	0.248	1.188	0.209	0.407
 *Berger 140 Hunting VLD*	0.248	0.970	0.256	0.498
 *Berger 168 Classic Hunter*	0.298	1.026	0.290	0.565
 *Berger 168 Hunting VLD*	0.298	0.941	0.316	0.616
 *Berger 180 Hunting VLD*	0.319	0.925	0.345	0.671
 *Berger 195 Hunting Hybrid*	0.345	0.893	0.387	0.754
 *Berger 168 Target VLD*	0.298	0.926	0.322	0.626

(.284 caliber bullets continued)				
Bullet	**SD**	i_7	**G7 BC**	**G1 BC**
 *Berger 180 Target Hybrid*	0.319	0.915	0.349	0.679
 *Berger 180 Target VLD*	0.319	0.912	0.350	0.681
 *Cauterucio 177 VLD*	0.314	0.897	0.349	0.681
 *Cauterucio 189 VLD*	0.335	0.930	0.360	0.701
 *GS Custom 125 SP*	0.221	1.188	0.187	0.364
 *Hornady 162 Amax*	0.287	0.936	0.307	0.598
 *Hornady 162 BTHP Match*	0.287	0.966	0.297	0.578
 *Hornady 139 GMX*	0.246	1.102	0.224	0.437
 *Hornady 139 Interbond*	0.246	0.993	0.248	0.485
 *Hornady 154 Interbond*	0.273	1.001	0.273	0.533
 *Hornady 175 Interlock*	0.310	1.314	0.236	0.459
 *Hornady 139 BTSP Interlock*	0.246	1.207	0.204	0.397

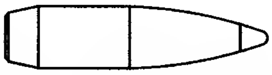
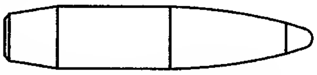
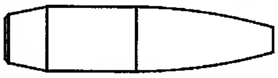
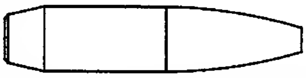
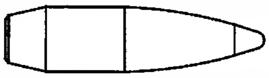
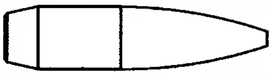
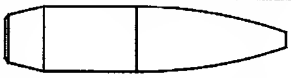
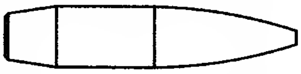
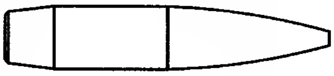
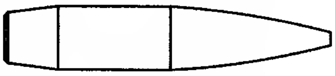
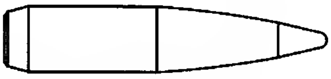
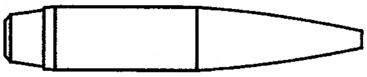
(.284 caliber bullets continued)

Bullet	SD	i_7	G7 BC	G1 BC
 *Hornady 162 BTSP Interlock*	0.287	1.165	0.246	0.480
 *Hornady 139 SP Interlock*	0.246	1.261	0.195	0.380
 *Hornady 154 SP Interlock*	0.273	1.300	0.210	0.409
 *Hornady 139 SST BT*	0.246	1.068	0.231	0.451
 *Hornady 154 SST BT*	0.273	1.086	0.251	0.491
 *Hornady 162 SST BT*	0.287	1.048	0.274	0.535
 *Hornady 120 Vmax*	0.213	1.155	0.184	0.359
 *JLK 180 BTHP*	0.319	0.966	0.330	0.643
 *Lapua 150 Scenar L*	0.266	0.911	0.268	0.522
 *Lapua 180 Scenar L*	0.319	0.999	0.319	0.621
 *Matrix 175 RBT*	0.310	1.096	0.283	0.551
 *Matrix 168 VLD*	0.298	0.956	0.311	0.606

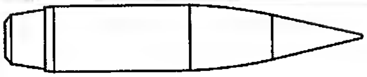
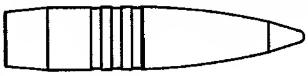
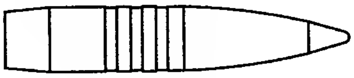
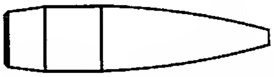
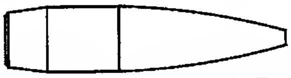
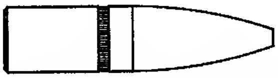
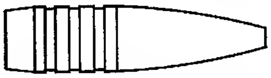
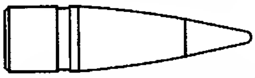
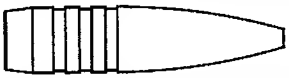
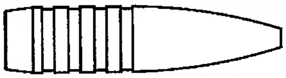
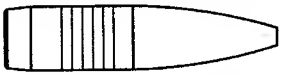
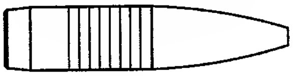
(.284 caliber bullets continued)

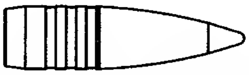
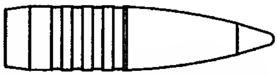
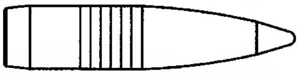
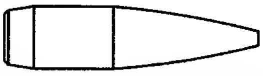
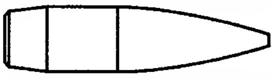
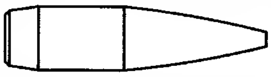
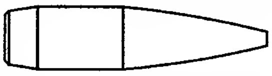
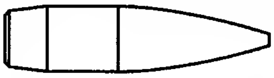
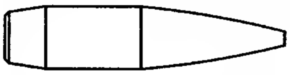
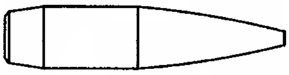
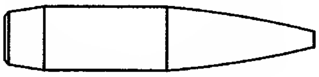
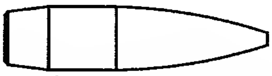
Bullet	SD	i7	G7 BC	G1 BC
 *Matrix 190 VLD*	0.337	0.978	0.344	0.670
 *Nosler 150 LR Accubond*	0.266	0.902	0.295	0.575
 *Nosler 168 LR Accubond*	0.298	0.896	0.332	0.648
 *Nosler 175 LR Accubond*	0.310	0.940	0.330	0.643
 *Nosler 140 Ballistic Silver Tip*	0.248	1.163	0.213	0.417
 *Nosler 120 Ballistic Tip*	0.213	1.137	0.187	0.365
 *Nosler 150 Ballistic Tip*	0.266	1.131	0.235	0.458
 *Nosler 168 Custom Competition*	0.298	1.106	0.269	0.524
 *Nosler 140 E-Tip*	0.248	1.200	0.207	0.405
 *Nosler 150 E-Tip*	0.266	1.204	0.221	0.432
 *Nosler 150 Partition*	0.266	1.256	0.211	0.411
 *Nosler 175 Partition*	0.310	1.265	0.245	0.477

(.284 caliber bullets continued)

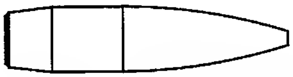
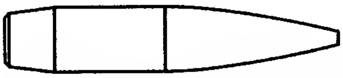
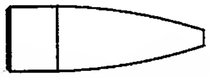
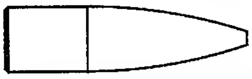
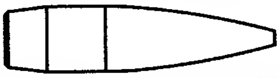
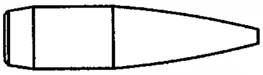
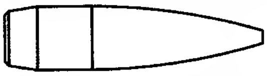
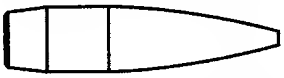
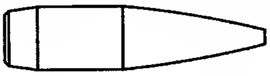
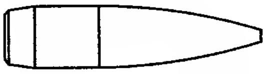
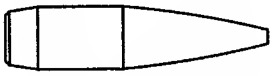
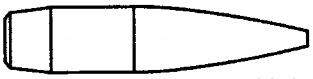
Bullet	SD	i_7	G7 BC	G1 BC
 *Sierra 150 GameKing*	0.266	1.209	0.220	0.428
 *Sierra 175 GameKing*	0.310	1.058	0.293	0.570
 *Sierra 140 HPBT GameKing*	0.248	1.356	0.183	0.356
 *Sierra 160 HPBT GameKing*	0.283	1.350	0.210	0.409
 *Sierra 140 SBT GameKing*	0.248	1.198	0.207	0.404
 *Sierra 130 MatchKing*	0.230	1.133	0.203	0.397
 *Sierra 150 MatchKing*	0.266	1.144	0.232	0.454
 *Sierra 168 MatchKing*	0.298	1.030	0.289	0.563
 *Sierra 175 MatchKing*	0.310	0.948	0.327	0.637
 *Sierra 180 MatchKing*	0.319	0.946	0.337	0.657
 *Swift 150 Scirocco II*	0.266	1.100	0.242	0.474
 *Wildcat 200 ULD*	0.354	0.985	0.360	0.700

.308 Caliber (7.62mm) bullets

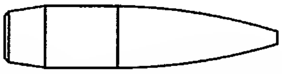
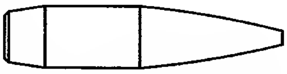
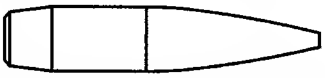
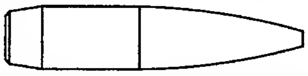
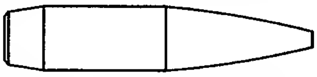
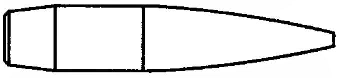
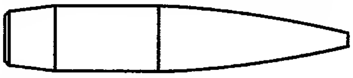
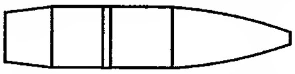
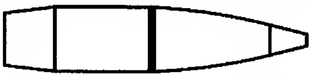
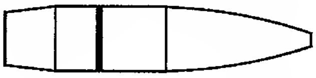
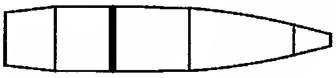
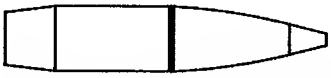
Bullet	SD	i_7	G7 BC	G1 BC
 Alco 220 Tipped RBBT	0.331	1.029	0.322	0.630
 Barnes 175 LRXBT	0.264	1.068	0.247	0.481
 Barnes 200 LRXBT	0.301	1.070	0.281	0.549
 Barnes 155 Match Burner	0.233	0.977	0.239	0.465
 Barnes 175 Match Burner	0.264	0.989	0.266	0.519
 Barnes 150 Tac RRLP FB	0.226	1.255	0.180	0.351
 Barnes 150 Tac-X BT	0.226	1.170	0.193	0.376
 Barnes 110 Tac-X FB M/LE	0.166	1.200	0.138	0.270
 Barnes 168 Tac-X M/LE	0.253	1.182	0.214	0.417
 Barnes 165 TSX BT	0.249	1.255	0.198	0.385
 Barnes 168 TSX BT	0.253	1.264	0.200	0.390
 Barnes 180 TSX BT	0.271	1.197	0.227	0.441

(.308 caliber (7.62mm) bullets continued)				
Bullet	**SD**	**i_7**	**G7 BC**	**G1 BC**
 *Barnes 130 TTSXBT*	0.196	1.128	0.174	0.339
 *Barnes 150 TTSXBT*	0.226	1.142	0.198	0.386
 *Barnes 168 TTSX BT*	0.253	1.086	0.233	0.454
 *Berger 155 Hunting VLD*	0.233	0.981	0.238	0.464
 *Berger 168 Classic Hunter*	0.253	1.010	0.251	0.488
 *Berger 168 Hunting VLD*	0.253	0.992	0.255	0.497
 *Berger 175 Hunting VLD*	0.264	0.995	0.265	0.516
 *Berger 185 Classic Hunter*	0.279	1.021	0.273	0.532
 *Berger 185 Hunting VLD*	0.279	0.976	0.285	0.556
 *Berger 190 Hunting VLD*	0.286	0.987	0.290	0.565
 *Berger 210 Hunting VLD*	0.316	0.989	0.320	0.623
 *Berger 175 Tactical OTM*	0.264	1.002	0.263	0.512

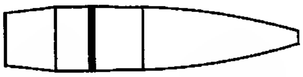
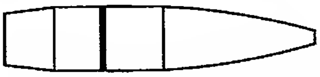
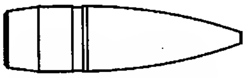
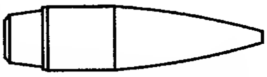
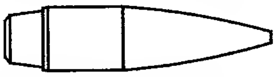
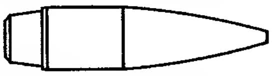
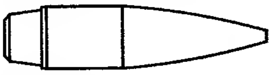
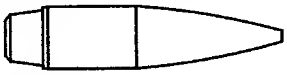
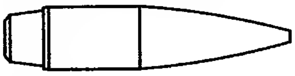
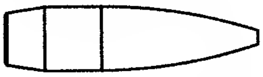
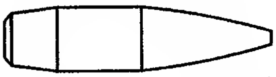
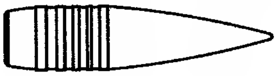
(.308 caliber (7.62mm) bullets continued)

Bullet	SD	i_7	G7 BC	G1 BC
 *Berger 185 Tactical OTM Juggernaut*	0.279	0.986	0.283	0.551
 *Berger 230 Tactical OTM Hybrid*	0.346	0.953	0.364	0.708
 *Berger 115 Target FB*	0.173	1.168	0.148	0.289
 *Berger 150 Target FB*	0.226	1.124	0.201	0.392
 *Berger 155 Target Hybrid*	0.233	0.953	0.245	0.477
 *Berger 155 Target VLD*	0.233	0.981	0.238	0.464
 *Berger 155.5 Fullbore*	0.234	0.968	0.241	0.470
 *Berger 168 Target Hybrid*	0.253	0.960	0.263	0.513
 *Berger 168 Target VLD*	0.253	0.973	0.260	0.507
 *Berger 175 Target Long Range BT*	0.264	1.005	0.262	0.511
 *Berger 175 Target VLD*	0.264	1.006	0.262	0.511
 *Berger 185 Target Hybrid*	0.279	0.945	0.295	0.575

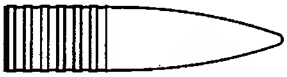
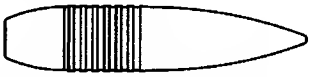
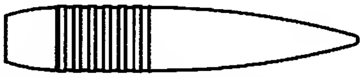
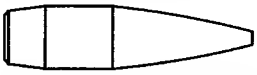
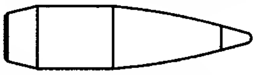
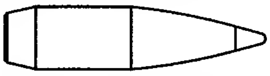
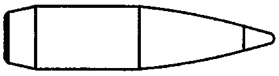
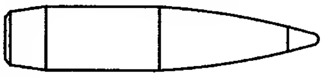
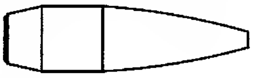
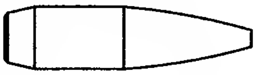
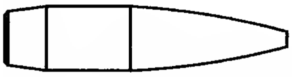
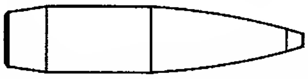
(.308 caliber (7.62mm) bullets continued)

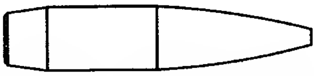
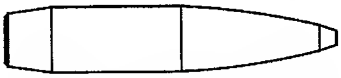
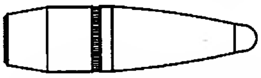
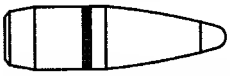
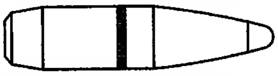
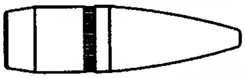
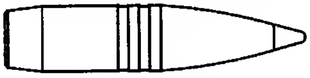
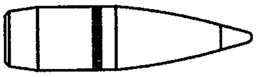
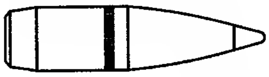
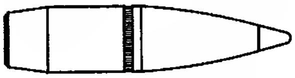
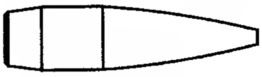
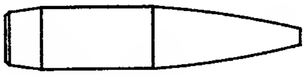
Bullet	SD	i_7	G7 BC	G1 BC
 *Berger 185 Target Long Range BT*	0.279	0.981	0.284	0.554
 *Berger 185 Target VLD*	0.279	1.002	0.278	0.542
 *Berger 200 Target Hybrid*	0.301	0.955	0.316	0.615
 *Berger 210 Target Long Range BT*	0.316	0.988	0.320	0.624
 *Berger 210 Target VLD*	0.316	0.995	0.318	0.619
 *Berger 215 Target Hybrid*	0.324	0.915	0.354	0.689
 *Berger 230 Target Hybrid*	0.346	0.942	0.368	0.717
 *Cutting Edge 180 HPBT*	0.271	1.108	0.245	0.477
 *Cutting Edge 165 Lazer*	0.249	1.005	0.247	0.482
 *Cutting Edge 180 LRHPBT-MAX*	0.271	1.041	0.260	0.507
 *Cutting Edge 180 LZR 180 MAX*	0.271	0.973	0.279	0.543
 *Cutting Edge 180 Lazer 180 STD*	0.271	1.008	0.269	0.524

(.308 caliber (7.62mm) bullets continued)

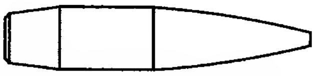
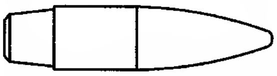
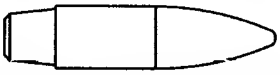
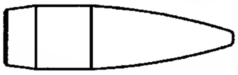
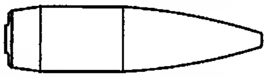
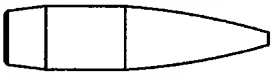
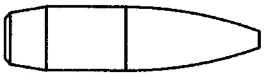
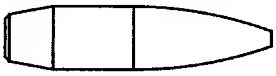
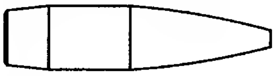
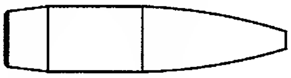
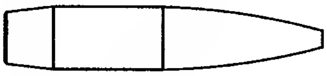
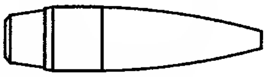
Bullet	SD	i_7	G7 BC	G1 BC
 *Cutting Edge 165 MTH*	0.249	0.972	0.256	0.498
 *Cutting Edge 180 MTH C21*	0.271	0.959	0.283	0.551
 *DAG 147 FMJ BT*	0.221	1.020	0.217	0.423
 *Dietlein 155.5 ULD*	0.234	1.004	0.233	0.455
 *Dietlein 168 ULD*	0.253	1.001	0.253	0.493
 *Dietlein 173 ULD*	0.261	1.070	0.243	0.475
 *Dietlein 175 ULD*	0.264	1.069	0.246	0.481
 *Dietlein 185 ULD*	0.279	1.023	0.272	0.531
 *Dietlein 190 ULD*	0.286	1.027	0.279	0.544
 *DRT 175 Frangible (non-lead)*	0.264	1.113	0.237	0.462
 *DRT 200 Frangible (non-lead)*	0.301	1.020	0.295	0.575
 *GS Custom 137 SP*	0.206	1.023	0.202	0.395

(.308 caliber (7.62mm) bullets continued)

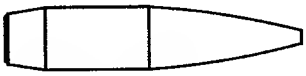
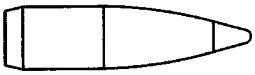
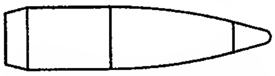
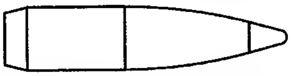
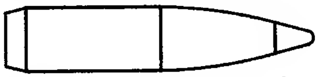
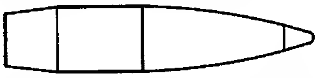
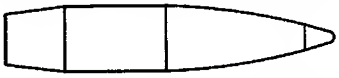
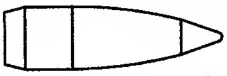
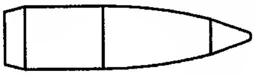
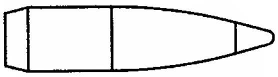
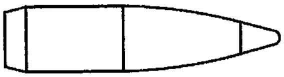
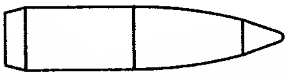
Bullet	SD	i_7	G7 BC	G1 BC
 GS Custom 158 SP	0.238	1.335	0.178	0.348
 GS Custom 167 SP	0.252	1.226	0.205	0.400
 GS Custom 197 SP	0.297	1.094	0.271	0.530
 155 HBC (Australia)	0.233	0.989	0.236	0.460
 Hornady 155 Amax	0.233	1.099	0.213	0.417
 Hornady 168 Amax	0.253	1.100	0.230	0.451
 Hornady 178 Amax	0.268	1.117	0.240	0.470
 Hornady 208 Amax	0.313	0.966	0.324	0.633
 Hornady 155 BTHP Match	0.233	1.133	0.206	0.403
 Hornady 168 BTHP Match	0.253	1.143	0.221	0.432
 Hornady 178 BTHP Match	0.268	1.043	0.257	0.501
 Hornady 195 BTHP Match	0.294	0.997	0.295	0.574

(.308 caliber (7.62mm) bullets continued)				
Bullet	**SD**	**i_7**	**G7 BC**	**G1 BC**
 *Hornady 208 BTHP Match*	0.313	0.982	0.319	0.621
 *Hornady 225 BTHP Match*	0.339	0.988	0.343	0.668
 *Hornady 165 BTSP Interlock*	0.249	1.224	0.203	0.395
 *Hornady 150 BTSP*	0.226	1.262	0.179	0.349
 *Hornady 190 BTSP*	0.286	1.205	0.237	0.463
 *Hornady 150 FMJBT*	0.226	1.100	0.205	0.400
 *Hornady 165 GMX*	0.316	1.111	0.224	0.437
 *Hornady 150 SST BT*	0.226	1.088	0.208	0.405
 *Hornady 165 SST BT*	0.249	1.110	0.224	0.437
 *Hornady 180 SST BT*	0.271	1.071	0.253	0.494
 *JLK 155 VLD*	0.233	0.981	0.238	0.464
 *JLK 210 VLD*	0.316	1.025	0.309	0.601

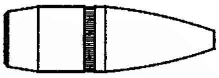
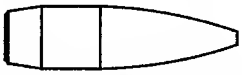
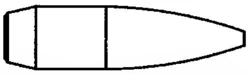
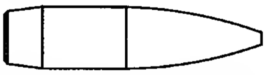
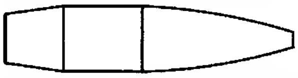
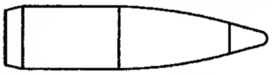
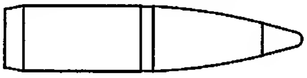
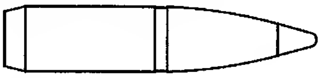
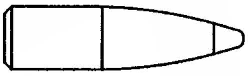
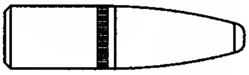
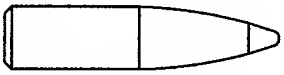
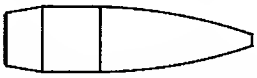
(.308 caliber (7.62mm) bullets continued)

Bullet	**SD**	**i_7**	**G7 BC**	**G1 BC**
 *JLK 210 VLD Long BT*	0.316	0.921	0.343	0.669
 *Lapua 185 FMJBT (D46)*	0.279	1.067	0.261	0.508
 *Lapua 200 FMJBT (subsonic)*	0.301	1.210	0.249	0.485
 *Lapua 150 FMJBT*	0.226	1.052	0.215	0.419
 *Lapua 170 FMJBT*	0.256	1.076	0.238	0.464
 *Lapua 155 Scenar*	0.233	0.988	0.236	0.461
 *Lapua 167 Scenar*	0.252	1.163	0.216	0.421
 *Lapua 185 Scenar*	0.279	1.130	0.246	0.480
 *Lapua 155 Scenar L*	0.233	1.056	0.221	0.431
 *Lapua 175 Scenar L*	0.264	1.067	0.247	0.481
 *Lapua 220 Scenar L*	0.331	1.033	0.321	0.624
 *Matrix 168 RBT*	0.253	1.056	0.240	0.466

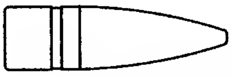
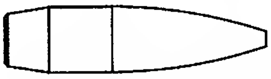
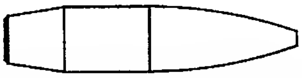
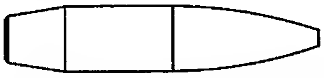
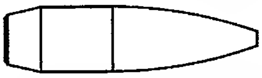
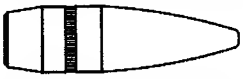
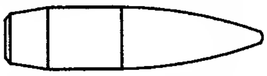
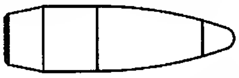
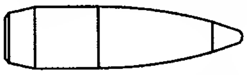
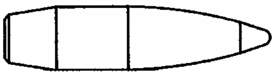
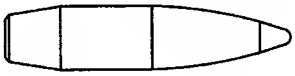
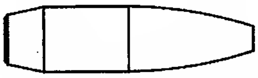
(.308 caliber (7.62mm) bullets continued)

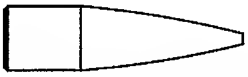
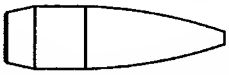
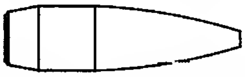
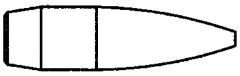
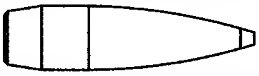
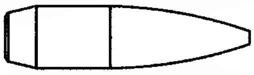
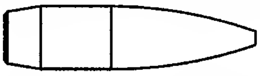
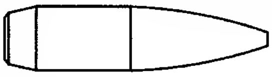
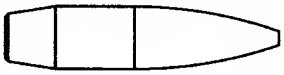
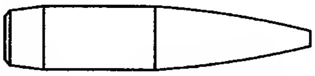
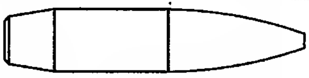
Bullet	SD	i_7	G7 BC	G1 BC
 *Matrix 210 VLD*	0.316	0.971	0.326	0.635
 *Nosler 150 Accubond*	0.226	1.146	0.197	0.386
 *Nosler 165 Accubond*	0.249	1.091	0.228	0.446
 *Nosler 180 Accubond*	0.271	1.101	0.247	0.482
 *Nosler 200 Accubond*	0.301	1.123	0.268	0.525
 *Nosler 190 Long Range Accubond*	0.286	0.981	0.292	0.569
 *Nosler 210 Long Range Accubond*	0.316	0.954	0.332	0.647
 *Nosler 125 Ballistic Tip*	0.188	1.127	0.167	0.327
 *Nosler 150 Ballistic Tip*	0.226	1.114	0.203	0.397
 *Nosler 165 Ballistic Tip*	0.249	1.094	0.227	0.445
 *Nosler 168 Ballistic Tip*	0.253	1.159	0.219	0.427
 *Nosler 180 Ballistic Tip*	0.271	1.125	0.241	0.472

(.308 caliber (7.62mm) bullets continued)

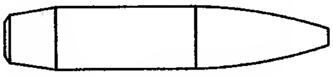
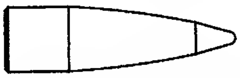
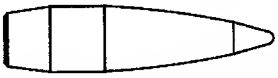
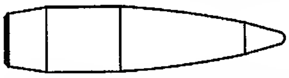
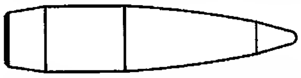
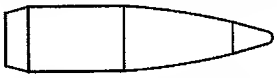
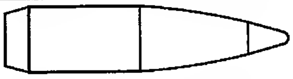
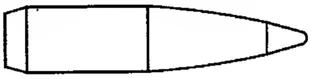
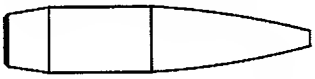
Bullet	SD	i_7	G7 BC	G1 BC
 *Nosler 140 Custom Competition*	0.211	1.271	0.166	0.323
 *Nosler 155 Custom Competition*	0.233	1.098	0.213	0.414
 *Nosler 168 Custom Competition*	0.253	1.159	0.218	0.427
 *Nosler 175 Custom Competition*	0.264	1.059	0.249	0.485
 *Nosler 190 Custom Competition*	0.286	1.030	0.278	0.541
 *Nosler 150 E-Tip*	0.226	1.193	0.189	0.370
 *Nosler 168 E-Tip*	0.253	1.159	0.218	0.427
 *Nosler 180 E-Tip*	0.271	1.208	0.225	0.439
 *Nosler 165 Partition*	0.249	1.218	0.204	0.397
 *Nosler 180 Partition*	0.271	1.475	0.184	0.358
 *Nosler 200 Partition*	0.301	1.210	0.249	0.485
 *155 PMP (South Africa)*	0.233	1.041	0.224	0.438

(.308 caliber (7.62mm) bullets continued)

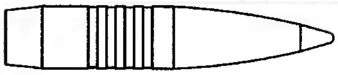
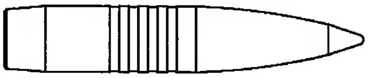
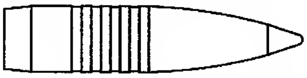
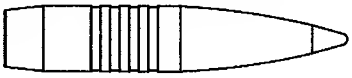
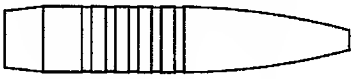
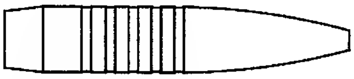
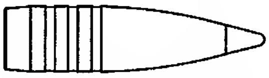
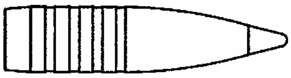
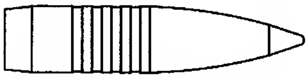
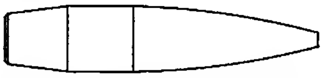
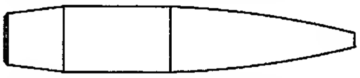
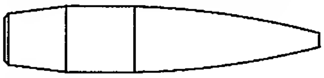
Bullet	SD	i_7	G7 BC	G1 BC
 *Prvi Partizan 150 FMJ*	0.226	1.146	0.197	0.384
 *RUAG Swiss Match 175 HPBT*	0.264	1.071	0.246	0.479
 *RUAG Swiss Match 200 HPBT*	0.301	1.061	0.284	0.553
 *RUAG Swiss Match 220 HPBT*	0.331	1.062	0.312	0.608
 *RUAG Swiss P Target 168 HPBT*	0.253	1.150	0.220	0.430
 *Sierra 150 FMJ BT*	0.226	1.091	0.207	0.403
 *Sierra 173 FMJ BT*	0.261	1.039	0.251	0.489
 *Sierra 150 GameKing*	0.226	1.189	0.190	0.371
 *Sierra 165 GameKing*	0.249	1.169	0.213	0.415
 *Sierra 180 GameKing*	0.271	1.120	0.242	0.472
 *Sierra 200 GameKing*	0.301	1.041	0.289	0.564
 *Sierra 165 HPBT GameKing*	0.249	1.397	0.178	0.347

(.308 caliber (7.62mm) bullets continued)				
Bullet	**SD**	**i_7**	**G7 BC**	**G1 BC**
 *Sierra 125 MatchKing*	0.188	1.063	0.177	0.346
 *Sierra 135 MatchKing*	0.203	1.116	0.182	0.356
 *Sierra 150 MatchKing*	0.226	1.128	0.200	0.391
 *Sierra 155 MatchKing Palma (2155)*	0.233	1.092	0.214	0.417
 *Sierra 155 MatchKing Palma (2156)*	0.233	0.985	0.237	0.462
 *Sierra 168 MatchKing*	0.253	1.160	0.218	0.426
 *Sierra 175 MatchKing*	0.264	1.085	0.243	0.473
 *Sierra 180 MatchKing*	0.271	1.099	0.247	0.482
 *Sierra 190 MatchKing*	0.286	1.070	0.267	0.521
No image available *Sierra 200 MatchKing*	0.301	1.058	0.285	0.555
 *Sierra 210 MatchKing*	0.316	1.000	0.316	0.616
 *Sierra 220 MatchKing*	0.331	1.068	0.310	0.604

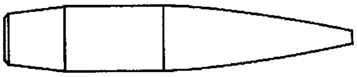
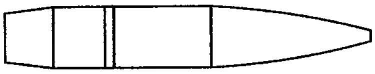
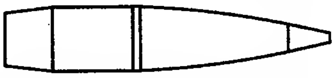
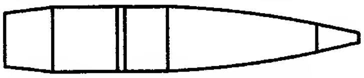
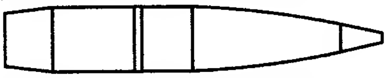
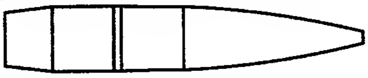
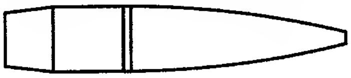
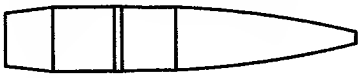
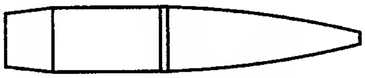
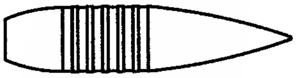
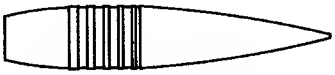
(.308 caliber (7.62mm) bullets continued)

Bullet	SD	i_7	G7 BC	G1 BC
 *Sierra 240 MatchKing*	0.361	1.093	0.331	0.644
 *Sierra 125 Tipped MatchKing*	0.188	1.070	0.176	0.344
 *Sierra 155 Tipped MatchKing*	0.233	0.983	0.238	0.464
 *Sierra 168 Tipped MatchKing*	0.253	0.984	0.257	0.503
 *Sierra 175 Tipped MatchKing*	0.264	0.991	0.266	0.520
 *Swift 150 BT Spitzer*	0.226	1.132	0.200	0.392
 *Swift 165 BT Spitzer*	0.249	1.126	0.221	0.433
 *Swift 180 BT Spitzer*	0.271	1.103	0.246	0.483
 *Vapor Trail 207 BTHP*	0.312	1.009	0.309	0.602

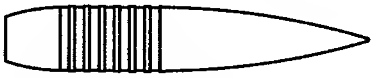
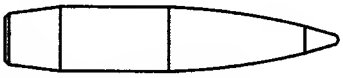
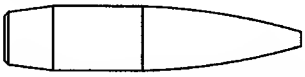
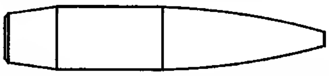
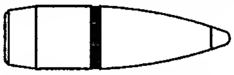
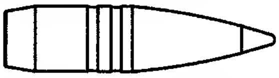
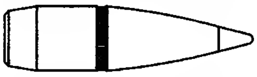
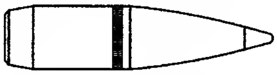
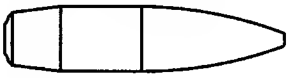
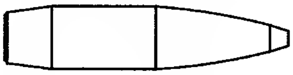
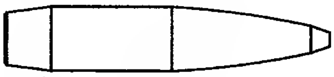
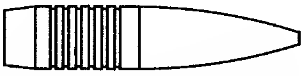
.338 Caliber bullets

Bullet	**SD**	**i_7**	**G7 BC**	**G1 BC**
 *Barnes 265 LRX BT*	0.331	1.069	0.310	0.605
 *Barnes 280 LRX BT*	0.350	1.086	0.322	0.629
 *Barnes 225 TAC-TX BT*	0.281	1.134	0.248	0.484
 *Barnes 265 TAC-TX BT*	0.331	1.108	0.299	0.583
 *Barnes 285 TAC-X BT*	0.356	1.168	0.306	0.594
 *Barnes 285 TSX BT*	0.356	1.180	0.302	0.588
 *Barnes 185 TTSX BT*	0.231	1.128	0.205	0.400
 *Barnes 210 TTSX BT*	0.263	1.132	0.232	0.453
 *Barnes 225 TTSX BT*	0.281	1.110	0.253	0.494
 *Berger 250 Elite Hunter*	0.313	0.891	0.351	0.684
 *Berger 300 Elite Hunter*	0.375	0.900	0.417	0.812
 *Berger 250 Tactical OTM*	0.313	0.895	0.349	0.680

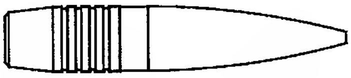
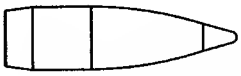
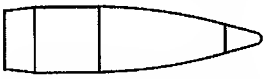
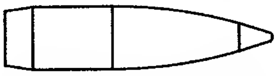
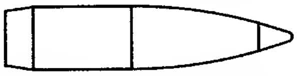
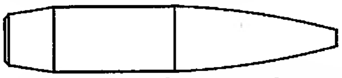
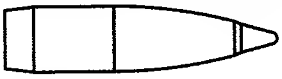
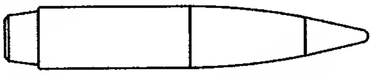
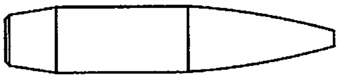
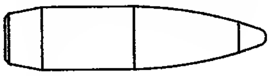
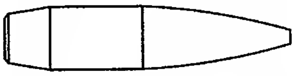
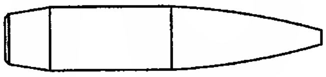
(.338 caliber bullets continued)

Bullet	SD	i_7	G7 BC	G1 BC
 *Berger 300 Tactical OTM*	0.375	0.900	0.417	0.812
 *Cutting Edge 300 HPBT*	0.375	0.927	0.405	0.789
 *Cutting Edge 225 Lazer*	0.281	0.902	0.312	0.609
 *Cutting Edge 250 Lazer*	0.313	0.877	0.357	0.696
 *Cutting Edge 275 Lazer*	0.344	0.860	0.400	0.780
Cutting Edge 254 MTAC	0.318	0.862	0.368	0.718
 *Cutting Edge 275 MTAC*	0.344	0.829	0.415	0.809
 *Cutting Edge 252 MTH*	0.315	0.860	0.366	0.714
 *Cutting Edge 265 MTH*	0.331	0.844	0.393	0.765
 *Cutting Edge 275 MTH*	0.344	0.834	0.412	0.804
 *GS Custom 200 SP*	0.250	1.147	0.218	0.426
 *GS Custom 232 SP*	0.290	0.995	0.292	0.570

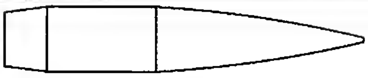
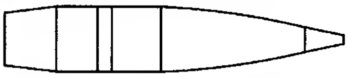
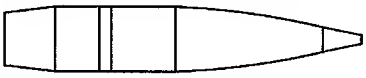
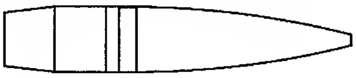
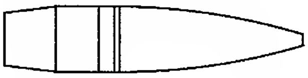
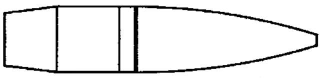
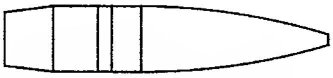
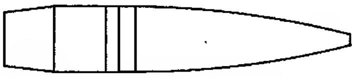
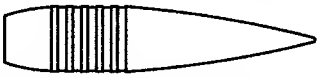
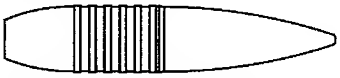
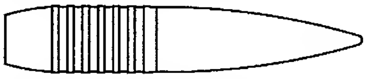
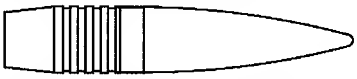
(.338 caliber bullets continued)

Bullet	SD	i_7	G7 BC	G1 BC
 GS Custom 267 SP	0.334	1.102	0.304	0.593
 Hornady 285 Amax	0.356	0.945	0.377	0.736
 Hornady 250 BTHP Match	0.313	0.970	0.322	0.628
 Hornady 285 BTHP Match	0.356	0.997	0.357	0.696
 Hornady 200 FXT	0.250	1.170	0.214	0.417
 Hornady 185 GMX	0.231	1.122	0.206	0.403
 Hornady 200 SST	0.250	1.062	0.236	0.461
 Hornady 225 SST	0.281	1.060	0.266	0.519
 Lapua 250 FMJBT	0.313	1.015	0.308	0.600
 Lapua 250 Scenar	0.313	1.025	0.305	0.594
 Lapua 300 Scenar	0.375	0.956	0.392	0.764
 Lehigh 230 Match Solid	0.288	1.018	0.282	0.551

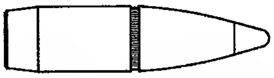
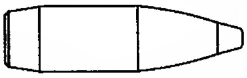
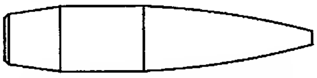
(.338 caliber bullets continued)

Bullet	SD	i_7	G7 BC	G1 BC
 *Lehigh 245 Match Solid*	0.306	0.866	0.354	0.690
 *Nosler 180 Accubond*	0.225	1.077	0.209	0.408
 *Nosler 200 Accubond*	0.250	1.060	0.236	0.461
 *Nosler 225 Accubond*	0.281	1.049	0.268	0.524
 *Nosler 250 Accubond*	0.313	1.049	0.298	0.582
 *Nosler 300 Custom Competition*	0.375	1.017	0.369	0.718
 *Nosler 200 E-Tip*	0.250	1.125	0.222	0.434
 *Rocky Mountain 325 RBT*	0.406	1.052	0.386	0.754
 RUAG Swiss P 300	0.375	0.990	0.379	0.738
 *Sierra 250 Game King*	0.313	1.177	0.266	0.518
 *Sierra 250 MatchKing*	0.313	0.996	0.314	0.612
 *Sierra 300 MatchKing*	0.375	0.986	0.380	0.742

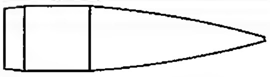
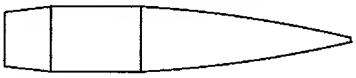
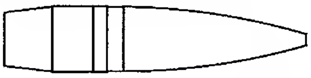
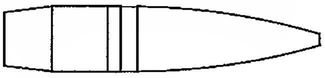
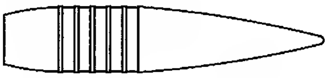
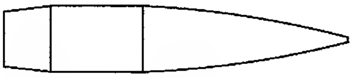
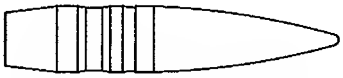
.375 Caliber bullets

Bullet	SD	i_7	G7 BC	G1 BC
 *Chey Tac 350 Solid*	0.356	0.843	0.422	0.822
 *Cutting Edge 325 Lazer*	0.330	0.892	0.370	0.722
 *Cutting Edge 350 Lazer*	0.356	0.905	0.393	0.767
 *Cutting Edge 352 MTAC*	0.358	0.876	0.408	0.796
 *Cutting Edge 300 MTH*	0.305	0.921	0.331	0.645
 *Cutting Edge 320 MTH*	0.325	0.929	0.350	0.682
 *Cutting Edge 330 MTH*	0.355	0.873	0.384	0.749
 *Cutting Edge 350 MTH*	0.356	0.856	0.415	0.810
 *GS Custom 291 SP*	0.296	1.044	0.284	0.555
 *GS Custom 330 SP*	0.335	1.128	0.297	0.581
 *GS Custom 355 SP*	0.361	1.069	0.338	0.660
 *Lehigh 330 Match Solid*	0.335	0.861	0.390	0.761

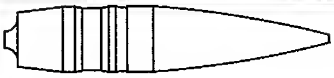
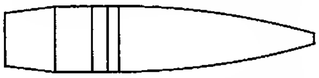
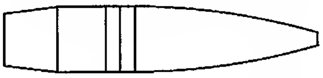
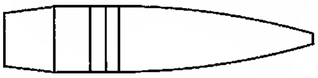
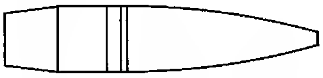
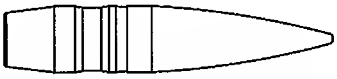
(.375 caliber bullets continued)

Bullet	SD	i_7	G7 BC	G1 BC
 *Nosler 300 Accubond*	0.305	1.205	0.253	0.493
 *Sierra 300 GameKing*	0.305	1.305	0.234	0.455
 *Sierra 350 MatchKing*	0.356	0.947	0.375	0.732

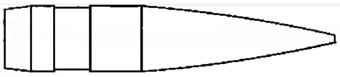
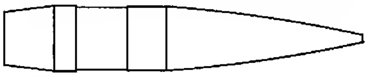
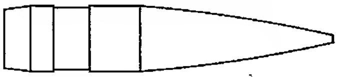
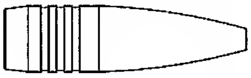
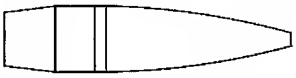
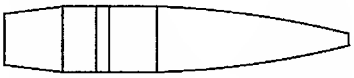
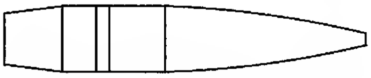
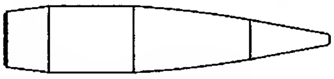
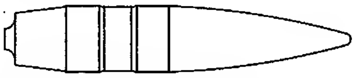
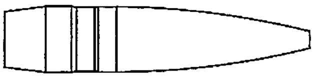
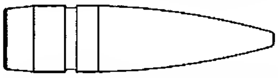
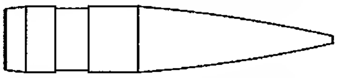
.408 Caliber bullets

Bullet	SD	i_7	G7 BC	G1 BC
 *Chey Tac 305 Solid*	0.262	0.940	0.279	0.545
 *Chey Tac 419 Solid*	0.360	0.833	0.432	0.845
 *Cutting Edge 390 MTH*	0.335	0.898	0.373	0.727
 *Cutting Edge 415 MTH*	0.356	0.872	0.408	0.796
 *GS Custom 385 gr SP*	0.330	1.029	0.322	0.629
 *HSM 400 T50 Solid*	0.343	0.795	0.432	0.844
 *Lehigh 400 Match Solid*	0.343	0.868	0.396	0.772

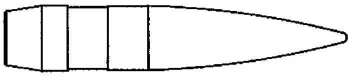
.416 Caliber bullets

Bullet	SD	i_7	G7 BC	G1 BC
 *Barrett 398 Brass Solid*	0.329	0.920	0.357	0.697
 *Cutting Edge 422 MTAC*	0.348	0.850	0.410	0.799
 *Cutting Edge 446 MTAC*	0.368	0.923	0.399	0.777
 *Cutting Edge 420 MTH*	0.347	0.862	0.402	0.785
 *Cutting Edge 444 MTH*	0.367	0.928	0.395	0.770
 *Lehigh 416 Solid Match*	0.343	0.881	0.390	0.761

.510 Caliber bullets

Bullet	SD	i_7	G7 BC	G1 BC
 *Barnes 750 LR Solid Bore*	0.412	0.901	0.458	0.894
 *Barnes 800 LR Solid*	0.439	0.908	0.484	0.946
 *Barnes 750 TAC-LR*	0.412	0.958	0.431	0.841
 *Barnes 647 TAC-X/TSX*	0.355	1.181	0.301	0.586
 *Cutting Edge 720 MTAC_X03*	0.396	0.922	0.429	0.836
 *Cutting Edge 762 MTAC_X02*	0.419	0.859	0.487	0.950
 *Cutting Edge 802 MTAC_X01*	0.441	0.888	0.496	0.967
 *Hornady 750 Amax*	0.412	0.811	0.508	0.991
 *Lapua 800 Bullex-N*	0.439	0.889	0.494	0.964
 *Leigh 750 Controlled Chaos*	0.412	0.889	0.463	0.904
 *Lehigh 650 Solid Match*	0.357	0.889	0.402	0.784
 *Lehigh 750 Solid Match*	0.412	1.002	0.412	0.804

(.510 caliber bullets continued)

Bullet	**SD**	**i_7**	**G7 BC**	**G1 BC**
 *Lehigh 808 solid Match*	0.444	0.984	0.452	0.882

Appendix B

Appendix B lists all of the equations used in this book along with explanations of the variables and examples of how to make use of the equations in spreadsheet programs like Microsoft Excel.

Instead of displaying the derivation of these equations in full mathematical rigor, I'll provide some practical information about how and when the equation might be useful and how to properly apply it.

Equation 2.1: The Ballistic Coefficient

$$BC = \frac{W/7000}{cal^2 \cdot i} \left(\frac{lb}{in^2}\right)$$

Where:

BC is the ballistic coefficient in lb/in^2
W is the bullet weight in grains
cal is the bullet caliber in inches
i is the bullets form factor, which is unitless

Comments:
The form factor i can be referenced to one of many standards. The two used in this book are G1 and G7. BCs and form factors are subscripted with either a 1 or a 7 to indicate what standard they're being referenced to.

Example:
For a .308 caliber 155 grain bullet with a G7 form factor of 1.05:

$$BC_7 = \frac{155/7000}{0.308^2 \cdot 1.05} \left(\frac{lb}{in^2}\right) = 0.222 \left(\frac{lb}{in^2}\right)$$

Spreadsheet format:

BC =(155/7000)/(0.308^2*1.05)

The ballistic coefficient.

Equation 2.2: The Form Factor

$$i = \frac{cd}{cd_{ST}}$$

Where:

i is the bullet's form factor, which is unitless

cd is the drag coefficient of a bullet at some speed

cd_{ST} is the drag coefficient of a standard bullet (G1, G7, etc) at the same speed.

Comments:

The form factor is significant because it relates the drag of a bullet to the drag of a standard bullet. The form factor is required in order to calculate a Ballistic Coefficient.

It's difficult to determine the actual drag coefficient of a given bullet at some speed. The drag coefficients of the G1 and G7 standard projectiles are known and constant quantities given in the table below.

Example:

Consider a bullet that has a drag coefficient of 0.250 at Mach 3.0 (3360 fps in the standard atmosphere). First, calculate the form factor of this bullet for the G1 standard.The drag coefficient of the G1 standard projectile at Mach 3 is 0.513.

$$i_1 = \frac{0.250}{0.513} = 0.487$$

Next, calculate the *G7* form factor for this bullet. The drag coefficient of the G7 standard projectile at Mach 3 is 0.242.

$$i_7 = \frac{0.250}{0.242} = 1.033$$

Mach	G1 CD	G7 CD
0.00	0.263	0.120
0.50	0.203	0.119
0.60	0.203	0.119
0.70	0.217	0.120
0.80	0.255	0.124
0.90	0.342	0.146
0.95	0.408	0.205
1.00	0.481	0.380
1.05	0.543	0.404
1.10	0.588	0.401
1.20	0.639	0.388
1.30	0.659	0.373
1.40	0.663	0.358
1.50	0.657	0.344
1.60	0.647	0.332
1.80	0.621	0.312
2.00	0.593	0.298
2.20	0.569	0.286
2.50	0.540	0.270
3.00	0.513	0.242
3.50	0.504	0.215
4.00	0.501	0.194

Equation 5.1: Lag Time

$$T_{lag} = tof - tof_{vac}$$

Where:

T_{lag} = Lag Time (seconds)
tof = Actual bullet time of flight (seconds)
tof_{vac} = Theoretical vacuum time of flight (seconds)

Comments:

Lag time is important because it is the fundamental measure that determines how sensitive a bullet will be to wind deflection. A bullet's muzzle velocity and BC will determine how much lag time the bullet will have at a given range.

Example:

Consider a bullet that has a muzzle velocity of 3000 fps, fired at a target 600 yards away. According to a ballistics program, the bullet will have a time of flight of 0.7448 seconds. This is considered the bullets *actual* time of flight. To calculate the vacuum time of flight, simply divide the range (in feet) by the bullets muzzle velocity.

$$tof_{vac}=1800/3000=0.6000 \text{ seconds}$$

Now you can apply the lag time equation:

$$T_{lag} = 0.7448–0.6000 = 0.1448 \text{ seconds}$$

Lag time.

Equation 5.2: Wind Deflection

$$W_d = 17.6 * W_s * T_{lag}$$

Where:

Wd = wind deflection (inches)
Ws = crosswind speed (mph)
T_{lag} = Lag time (seconds)

Comments:

For winds that are not perfect crosswinds, you have to determine the *crosswind component.* A wind from 2, 4, 8 and 10 o'clock will have a crosswind component that's equal to 0.87 times its actual speed. For example, a 10 mph wind from 4 o'clock has an 8.7 mph crosswind component. Winds from 1, 5, 7, and 11 o'clock have a crosswind component equal to ½ their full value.

The wind deflection predicted by this equation is an exact mathematical solution to wind deflection. You can check it against the output of a ballistics program.

Although it's simple and exact, this equation doesn't have much practical use. You need the bullet's actual time of flight to get the lag time, and you need a ballistics program to get the bullet's actual time of flight. If you have a ballistics program to get time of flight, you can just calculate wind deflection with the program! In other words, the wind deflection formula is what's used (in one form or another) in the ballistics programs.

Example:

Consider a bullet with a lag time of 0.3731 seconds at 600 yards (as in the previous example) flying thru a 10 mph crosswind. How many inches will that bullet be deflected by the crosswind?

$$W_d = 17.6 * W_s * T_{lag}$$
$$W_d = 17.6 * 10 * 0.1448$$
$$W_d = 25.5 \text{ inches}$$

Wind Deflection.

Equation 5.3: Velocity

$$V_2 = V_1\sqrt{\frac{W_1}{W_2}}$$

Where:

V_2 = velocity of bullet 2 (fps)
V_1 = velocity of bullet 1 (fps)
W_2 = Weight of bullet 2 (grains)
W_1 = Weight of bullet 1 (grains)

Comments:

This equation for velocity can be used to *project* the velocity of a bullet based on the velocity of another bullet. This is useful because it allows you to estimate how much velocity you can get from a heavier or lighter bullet in a given chambering. For example, if you know your .308 Winchester can achieve 3000 fps with 155 grain bullets, you can use this equation to figure out how fast you can expect to shoot 185 grain bullets with the same amount of chamber pressure.

Example:

Let's calculate the expected velocity of a 185 grain .308 bullet. The 155 grain bullet is capable of 3000 fps. By applying Equation 4.4, you can determine what velocity ofa 185 grain bullet that's fired with the same chamber pressure.

$$V = 3000\sqrt{\frac{155}{185}}$$

$$V = 2746 fps$$

This method is based on the assumption that the heavy and light bullets emerge from the muzzle with the same kinetic energy, which is a good assumption, but not necessarily perfect.

This method of estimating muzzle velocity is useful when comparing the ballistic performance of two bullet weights for a given cartridge.

Spreadsheet format:

V =sqrt(3000^2*155/185)

Velocity.

Equation 5.4: Aerodynamic Jump

$$Y = 0.01 \cdot SG - 0.0024 \cdot L + 0.032$$

Where:

Y is the vertical deflection in MOA of a 1 mph crosswind
SG is the Gyroscopic Stability factor
L is the bullet length in calibers

Comments:

This equation calculates the vertical component of deflection for a crosswind. The basic result from the equation is a vertical deflection in MOA, per mph of crosswind. If there is a 10 mph wind from 1 O'clock, use only the crosswind component (in this case, 5 mph) for Equation 5.4.

Example:

Consider the Berger 7mm 180 grain VLD. According to the Miller Stability Formula, the SG of that bullet is 1.49 from a 1:9" twist barrel when fired at 2800 fps in standard conditions. The bullet is 1.517" long, which is 5.34 calibers in length (1.517/.284 = 5.34). Applying Equation 5.4 shows that we can expect:

$$Y = 0.01 \cdot 1.49 - 0.0024 \cdot 5.34 + 0.032 = 0.034 \frac{MOA}{MPH}$$

The deflection is down for a wind from the left, and up for a wind from the right for right twist barrels. The direction of the deflection is reversed for left twist barrels.

So if there is an 8 mph wind from the left, this bullet would be deflected down by 8*0.034 = 0.27 MOA down in addition to the horizontal wind deflection.

Spreadsheet format:

Y = 0.01*1.49-0.0024*5.34+0.032

Aerodynamic Jump

Equation 6.1: Spin Drift

$$Drift = 1.25(Sg + 1.2)tof^{1.83}$$

Where:

Drift is spin drift in inches (in the direction of rifling twist)

SG is the gyroscopic stability factor as predicted by the Miller twist rule.

tof is the bullet's time of flight

Comments:

Gyroscopic drift or *spin* drift is the systematic deviation of a bullet in the direction in which it's spinning (right for right twist barrels). Spin drift is minor for most shots under 1000 yards, but can grow to significant amounts at extended ranges. The gyroscopic stability factor (SG) and time of flight are required to calculate spin drift. These can be found using the included software.

Example:

Consider the spin drift of a bullet that has a time of flight of 1.6845 seconds. The range to the target is irrelevant when calculating spin drift (the range is accounted for thru time of flight). This bullet has a gyroscopic stability factor of 1.5.

$$Drift = 1.25(SG + 1.2)tof^{1.83}$$

$$Drift = 1.25(1.5 + 1.2)1.6845^{1.83}$$

$$Drift = 8.8\ inches$$

Spreadsheet format:

Drift =1.25*(1.5+1.2)*tof^1.83

Spin Drift.

Equation 9.1: Aperture Sight Calibration

$$1\,click = 171.89\frac{Sight\ movement\ for\ 20\ clicks(inches)}{Sight\ radius(inches)}MOA$$

Comments:

This equation is rather simple and self explanatory. It can be used to determine the actual movement of your point of aim for each click of an aperture sight based on the sight radius and the sight movement over 20 clicks as measured with a caliper.

It's a common mistake to *assume* that sight adjustments are what they're advertised to be (1/4 or ½ MOA per click). Chapter 9 has some illustrations showing exactly how to make the measurements needed to apply this equation.

Example:

Let's say the original position of the sight is 0.921" from the edge of the carrier. After moving the sight 20 clicks,it's 0.796" from the edge of the carrier. The sight moved a total of 0.125" over the 20 clicks. Now you measure the sight radius from the rear to the front aperture to be 35". Now plug these numbers into Equation 7.1:

$$1\,click = 171.89\frac{0.125}{35}MOA$$

$$1\,click = 0.614\,MOA$$

Aperture Sight Calibration.

Equation 12.1: Kinetic Energy

$$KE = \frac{BW \cdot V^2}{450800}$$

Where:

KE = Kinetic energy at the muzzle in foot-pounds
BW = bullet weight in grains
V = Velocity in feet per second

Comments:

Kinetic energy can be thought of as the bullets *striking energy.* Kinetic energy isn't important to target shooters who are just shooting at paper, but is very important to hunters who need to kill an animal. A common rule of thumb is that a bullet should strike with at least 1,000 ft-lb of kinetic energy to kill a white-tailed deer sized target.

Example:

Let's calculate the kinetic energy for a 155 grain bullet fired with a muzzle velocity of 3000 fps.

$$KE = \frac{155 \cdot 3000^2}{450800}$$

$$KE = 3094.5\, ft - lb$$

Now calculate the kinetic energy for that bullet at 500 yards. According to a ballistics program, the bullet will arrive at 500 yards with 2066 fps of velocity.

$$KE = \frac{155 \cdot 2066^2}{450800}$$

$$KE = 1467.6\, ft - lb$$

Spreadsheet format:

KE =155*2066^2/450800

Kinetic Energy.

Equation 15.1: Matunas' Optimal Game Weight Formula

$$OGW = V^3W^2 \cdot 1.5 \times 10^{-12}$$

Where:

OGW is the weight, in pounds, of the optimal weight of game that the bullet can/should be used for.
V is the velocity of the bullet in feet per second.
W is the weight of the bullet in grains.
$1.5\text{x}10^{-12}$ is a constant that takes care of the units.

Comments:
The *optimal game weight* is the weight of an animal that a bullet of a specific weight and velocity will be lethal on. It's important to remember that this equation is an approximation. Animals can certainly be killed at energy levels below those predicted by the OGW formula, but the shot will be below *optimal.* What that means is that the shot will rely on the animal dying from tissue damage alone (which may take time during which the animal can run) and there will be less of an instant incapacitation from hydrostatic shock.

Example:
What is the optimal game weight for a .308 that fires 155 grain bullets at 2850 fps?

$$\text{OGW} = 2850^3 * 155^2 * 1.5\text{X}10^{-12}$$

$$\text{OGW} = 834 \text{ pounds}$$

This is at the muzzle. In order to project the downrange optimal game weight, you have to calculate the downrange velocity and use that in the OGW equation.

Spreadsheet format:

OGW = 2850^3*155^2*1.5*10^-12

Matunas' optimal game weight formula.

Equation 19.1: G7 form factor prediction

$$\begin{gathered} i_7 = 1.470 - 0.346 \cdot A - \\ 0.162 \cdot B + \\ 0.018 \cdot C + 0.072 \cdot C^2 + \\ 2.520 \cdot D - 3.584 \cdot D^2 - \\ 0.171 \cdot E - \\ 0.111 \cdot F + 0.0118 \cdot F^2 - 0.000359 \cdot F^3 \end{gathered}$$

Equation 19.1

Where:

i_7 is the bullets form factor referenced to the G7 standard projectile
A is the bullet caliber in inches
B is the ogive length in calibers
C is the Rt/R ratio (unitless)
D is the meplat diameter in calibers
E is the length of the boat-tail in calibers
F is the angle of the boat-tail in degrees

Comments:

This equation can be used to predict the G7 form factor of a long range bullet (similar in shape to the G7 standard projectile) that is valid for all speeds. An example of how to use this equation to predict G7 form factor and BC is presented in Chapter 17. This formula is most efficiently applied in a spreadsheet, or some other kind of program that doesn't require keying in all of the variables each time. Doing so can easily lead to mistakes and should be avoided.

When accurate parameters of the bullet's geometry are used, the standard deviation of the error of Equation 17.1 is 2.1%. That means that the results will be accurate within +/- 4.2%; 95% of the time and accurate within +/- 6.3%; 99% of the time.

G7 form factor prediction.

The Miller Stability Formula

$$SG = \frac{30m}{t^2 d^3 l(1 + l^2)}$$

Where:

m is the bullet mass in grains
t is the rifling twist in *calibers per turn*
d is the diameter (caliber) of the bullet in inches
l is the length of the bullet in calibers

Comments:

This formula wasn't presented in the body of Chapter 10 on stability because I wanted to make the chapter about the *ideas* of stability and not the math. Here in the Appendix is where the math belongs. The Miller Stability Formula is very significant and represents a major modern advancement to the study of exterior ballistics for spin stabilized bullets. Don began publishing his twist rule around 2005. Before then the best thing shooters had to estimate gyroscopic stability was the antiquated Greenhill formula that was developed for *football* shaped projectiles at subsonic speed and is quite inaccurate for modern bullets.

The Miller formula has elevated the understanding and accuracy of stability calculations. The next page shows Miller's velocity and atmospheric corrections to the stability formula.

Example:

You know from Chapter 10 that the gyroscopic stability factor (SG) has to be 1.4 or higher. Consider a .308 caliber 155 grain bullet that's 1.2 inches long, and fired from a 1:13" twist barrel. What is the SG of that bullet?

$$SG = \frac{30(155)}{(13/0.308)^2 0.308^3 (1.2/0.308)(1 + (1.2/0.308)^2)}$$

$$SG = 1.42$$

Spreadsheet format:

`SG=(30*155)/((13/.308)^2*.308^3*1.2/.308*(1+(1.2/.308)^2))`

Miller Stability Formula.

The Miller Stability Formula: Velocity Correction

$$f_v = \left(\frac{V}{2800}\right)^{1/3}$$

Where:

f_v is the velocity correction factor
V is the muzzle velocity of the bullet

Comments:

The basic Miller stability factor formula given on the previous page is valid for a muzzle velocity of 2800 fps. In order to correct the equation for muzzle velocities other than 2800 fps, this f_v velocity correction factor is applied.

Example:

In the previous example, we calculated an SG of 1.42 for the 1.2" long .308 caliber 155 grain bullet. That SG is valid for 2800 fps, but what if we want to know how much the stability is affected by increasing the velocity to 3000 fps? First calculate the velocity correction factor:

$$f_v = \left(\frac{3000}{2800}\right)^{1/3} = 1.023$$

Now multiply the original SG by the correction factor:

$$Sg = 1.42 * 1.023 = 1.45$$

Spreadsheet format:

Velocity correction factor = (3000/2800)^(1/3)

Miller Stability Formula: Velocity Correction Factor.

The Miller Stability Formula: Atmospheric Correction

$$f_{tp} = \frac{(FT + 460)}{(59 + 460)} \frac{29.92}{PT}$$

Where:

f_{tp} is the temperature and pressure correction factor
FT is the air temperature in degrees Fahrenheit
PT is the air pressure in inches of mercury

Comments:

The atmospheric correction to the Miller stability factor formula accounts for the effects of air temperature and pressure on bullet stability. The correction factor f_{tp} is calculated and simply multiplies the SG found with the basic equation. If you are not as sea level, you must use the actual station or measured barometric pressure, not the Weather Bureau's sea-level corrected pressure.

Example:

We'll continue the previous example with the 1.2" long .308 caliber 155 grain bullet fired from a 1:13" twist. At 3000 fps, this bullet has a corrected SG of 1.45. What would be the SG of this bullet if the air temperature is 85°F, and the measured air pressure is 28.50 inHg? First calculate the correction factor:

$$f_{tp} = \frac{(85 + 460)}{(59 + 460)} \frac{29.92}{28.50} = 1.10$$

Now multiply the SG by the correction factor:

$$Sg = 1.45 * 1.10 = 1.60$$

Spreadsheet format:

Atmospheric correction factor = (85+460)/(59+460)*29.92/28.5

Miller Stability Formula: Atmospheric Correction Factor.

ICAO Standard Atmosphere

ICAO stands for *International Civil Aviation Organization* and it's the most up-to-date model of earth's atmosphere. It was established in 1962. The older Army Standard Metro atmosphere was developed in 1905 and has fallen out of use in most applications.

This table can be used to determine the ambient air pressure and temperature at altitudes from sea level to 10,000 ft. If you're making a drop chart for a hunting trip or rifle match you can use these atmospherics if you don't have the ability to measure and calculate the drop on site. The air pressure at altitude is pretty consistent year round with minor daily fluctuations as high and low pressure systems pass. Air pressure is not tied to the season. The air temperature is dictated by the season as well as the altitude.

Altitude (feet)	Air Pressure (inches of mercury)	Air Temperature (degrees Fahrenheit)
0	29.92	59
500	29.38	57
1000	28.86	55
1500	28.33	54
2000	27.82	52
2500	27.32	50
3000	26.82	48
3500	26.33	47
4000	25.84	45
4500	25.37	43
5000	24.90	41
5500	24.43	39
6000	23.98	38
6500	23.53	36
7000	23.09	34
7500	22.65	32
8000	22.23	31
8500	21.80	29
9000	21.39	27
9500	20.98	25
10000	20.58	23

ICAO standard atmosphere.

Definition of Speed of Sound

$$a = 49.0223\sqrt{FT + 459.67}$$

Where:

a is the speed of sound in fps.
FT is the air temperature in degrees Fahrenheit

Comments:
The formula given above is the ICAO definition for the speed of sound in dry air. Technically, Humidity has a slight affect on the speed of sound but is usually neglected because it's so small. For example, the speed of sound in 0% humidity and 59 degrees F is 1116.45 fps. At 100% humidity the speed of sound is 1119.1 fps at the same temperature, a difference of only 0.2%.

Example:
First calculate the speed of sound for the standard air temperature of 59 degrees F.

$$a = 49.0223\sqrt{59 + 459.67} = 1116.45\,fps$$

Next, calculate the speed of sound for an air temperature of 100 degrees F.

$$a = 49.0223\sqrt{100 + 459.67} = 1159.74\,fps$$

Spreadsheet format:
Speed of sound = 49.0223*sqrt(59+459.67)

ICAO definition of the speed of sound.

About the Book

Exterior ballistics is a very mature science. Unfortunately, most shooters have not been able to take full advantage of this field of knowledge because it's always been described in a highly technical language.

In this book, author, champion shooter and Ballistician Bryan Litz breaks down the complex science of accuracy into layman's terms that are easy to understand and apply. The objective of each subject matter is to present information to the reader which they can use to hit targets at long range.

Chapters include:
- The Ballistic Coefficient
- Wind Deflection
- Gyroscopic (Spin) Drift
- The Coriolis Effect
- Using Ballistics Programs
- Getting Control of Sights
- Bullet Stability
- Extended Range Shooting

Plus ballistic performance analysis for both long-range hunting and target shooting applications. Learn how the variables of long-range shooting affect your bullet and how to correct for them so your groups stay centered on target!

New for this Third Edition

The traditional role of exterior ballistics has been to account for the variables related to bullet flight so accurate fire solutions can be computed. Author Bryan Litz believes that ballistics has more to offer. Weapon Employment Zone (WEZ) analysis is the calculation of hit percentages.

New for this third edition, the subject of WEZ analysis is explored and some enlightening topics are presented regarding the effects of environmental uncertainties on your hit percentage, as well as how the ballistic performance of your rifle and bullet affects hit percentage as well.

This edition also includes the latest version of the Applied Ballistics Point Mass Solver on CD.

About the Author

Bryan Litz earned his Aerospace Engineering degree from Pennsylvania State University in 2002. For the next 6 years, he worked for the US Air Force on air-to-air missile design, modeling and simulation.
In 2008, Bryan became the Chief Ballistician for Berger Bullets. Bryan is also a very active and successful long-range shooter having won numerous regional, national, and international championships.

APPLIED BALLISTICS FOR LONG-RANGE SHOOTING

THIRD EDITION

BRYAN LITZ